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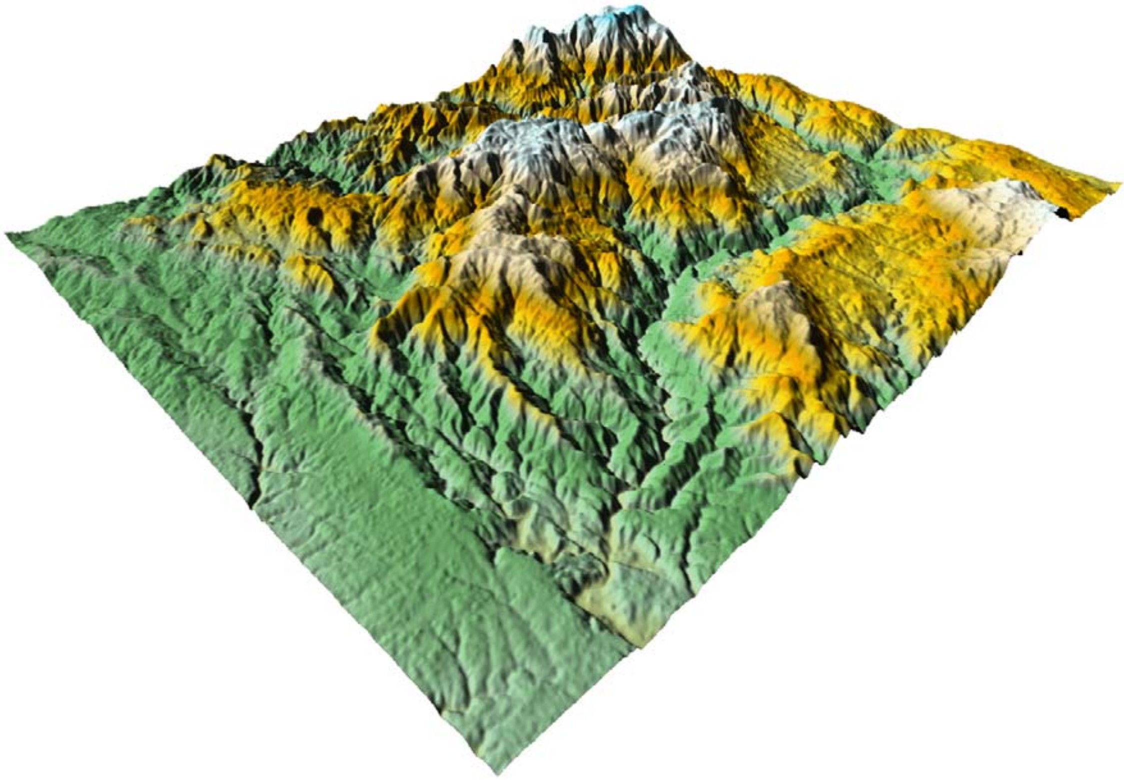
WAsP prediction errors due to site orography

Anthony J. Bowen and Niels G. Mortensen



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Title: WAsP prediction errors due to site orography
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Abstract (max. 2000 char.):
The influence of rugged terrain on the prediction accuracy of the Wind Atlas Analysis and Application Program (WAsP) is investigated using a case study of field measurements taken in rugged terrain. The parameters that could cause substantial errors in a prediction are identified and discussed. In particular, the effects from extreme orography are investigated. A suitable performance indicator is developed which predicts the sign and approximate magnitude of such errors due to orography. This procedure allows the user to assess the consequences of using WAsP outside its operating envelope and could provide a means of correction for rugged terrain effects.

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Cover
Surface plot of complex terrain in Northern Portugal, based on SRTM 3 arc-second elevation data. The plot covers an area of 39×45 km^2. Please refer to Section 5 for a description of the sites and experimental set-up.

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Preface

The results reported herein were obtained in 1995-96, using version 4 of the Wind Atlas Analysis and Application Program (WAsP). The WAsP program is now in version 8.1; however, the BZ flow model has not changed fundamentally during these years, so the analyses and conclusions presented below may still be considered generally valid for this type of linearised flow model.

No attempt has been made to update this edition to current knowledge – or to update the analyses using current data. Only a few figures have been improved, noticeably Figure 2 and the report cover which are now based on novel Shuttle Radar Topography Mission (SRTM) 3 arc-second elevation data.

Information about the current status and capabilities of the WAsP suite of programs may be obtained from www.wasp.dk and www.waspengineering.dk. It should be noted here though, that the ruggedness index proposed in Section 6 of the present report – now referred to as the RIX (Ruggedness IndeX) value – has been implemented in the most recent versions of the WAsP program. RIX values for every met. station (reference site) and turbine site (predicted site) in a WAsP workspace may thus be calculated, displayed and exported.

Niels G. Mortensen
December 2004

1 Introduction

The individual assumptions that were made during the development of the Wind Atlas Analysis and Application Program (WAsP) for the investigation of wind energy potential are well defined. The resulting limitations of the physical models that are used to cope with obstacles, surface roughness and orography have been pointed out in the User's Guide (Mortensen *et al.*, 1993b) and also in the literature. Although the program is based on atmospheric conditions which are predominantly neutrally stable, empirical corrections for mildly non-neutral conditions may also be applied through manipulation of the WAsP parameters. In view of the practical limitations imposed by climate and terrain, it is recommended that the proper use of the program is confined to terrain which may have low, smooth hills of small to moderate dimensions with sufficiently gentle slopes for areas of flow separation to be insignificant. The land area under scrutiny is also limited by the normal extent of the predominant weather patterns. Under these conditions, WAsP has been shown to be reliable and accurate. It has been used extensively to develop the European Wind Atlas (Troen and Petersen, 1989; Petersen *et al.*, 1995) and similar assessments of the wind energy resources in a number of other countries.

Out of necessity, WAsP is increasingly used for situations that do not lie within its recommended operational envelope. In particular, the program is being used for the investigation of candidate sites in rugged, complex terrain, which may also be subjected to intense solar radiation or stratified atmospheric conditions, see e.g. Botta *et al*. (1992), Bowen and Saba (1995), Reid (1995) and Sempreviva *et al*. (1986). Experience in the operation of commercial wind farms (Lindley *et al*., 1993) has confirmed that effects from the local complex terrain on the site characteristics of each turbine have a significant influence on the output (and perhaps even the viability) of a wind energy project. It is important that the WAsP user is aware of the likely errors from such predictions under these more extreme conditions and that some form of correction can be made if necessary.

The project reported here utilises full-scale wind data from a previous field programme in the rugged hills of northern Portugal to investigate the strengths and weaknesses of WAsP under such extreme conditions. The overall objective is to explore the operational limits of the WAsP models and to develop a strategy for estimating the accuracy of WAsP predictions for sites in complex terrain subjected to certain climatic and topographic situations.

The more detailed objectives of this project are:

a. Better understanding of prediction errors

   - Improvement of our understanding of the WAsP prediction error due to orography through the close scrutiny of the WAsP procedures and the use of reliable field case studies.

   - Identification of the significant parameters and how they affect the total prediction error.

b. Practical orographic performance indicator

   - Development of a suitable performance indicator, which would enable the prediction error to be estimated from site information.

- Confirmation of the performance indicator using a second independent case study.

c. Better prediction tools

   - Quantification of the orographic limits of the WAsP operating envelope for accurate results.
   - Provision of the means for correction of predictions when WAsP is used outside its operating envelope.

d. Further development

   - Provision of a better understanding of the physical process to enable the future improvement of the BZ orographic model.

2 The WAsP program

WAsP is a PC program that is used extensively to estimate wind energy resources and is described in detail by Troen and Petersen (1989) and others. The program can generalise a long-term meteorological data series at a (reference) site and may then be used to estimate conditions at a second (predicted) site within certain limits of climate and terrain.

The data generalisation is done through the WAsP Analysis procedure, which corrects the measured data series for local effects that only affect the reference site (met. station), but are not of more general nature.

These local effects are:

a. shelter from near-by obstacles such as houses and wind-breaks (obstacle model),
b. terrain surface roughness (roughness model), and
c. orography (BZ orographic flow model).

The generalised data are stored in the Atlas file which may then be used through the reverse process of the WAsP Application procedure in order to estimate the mean wind speeds and wind energy at a second (predicted) site, often referred to as a wind turbine site. A diagram showing the methodology of WAsP is shown in Figure 1.

2.1 Prediction accuracy

Accurate predictions using the WAsP package may be obtained provided that both the reference and predicted sites are clearly:

a. subject to the same weather regime, defined by the typical scale of the prevailing synoptic weather systems,
b. the prevailing weather conditions are close to being neutrally stable, and
c. the surrounding topography is not too steep, i.e. sufficiently gentle and smooth to ensure predominantly attached flows and minimal large-scale terrain effects such as channelling.

The prediction accuracy also depends on the quality of the reference data, the methods used by the user for preliminary data processing and the correct use of the WAsP program.

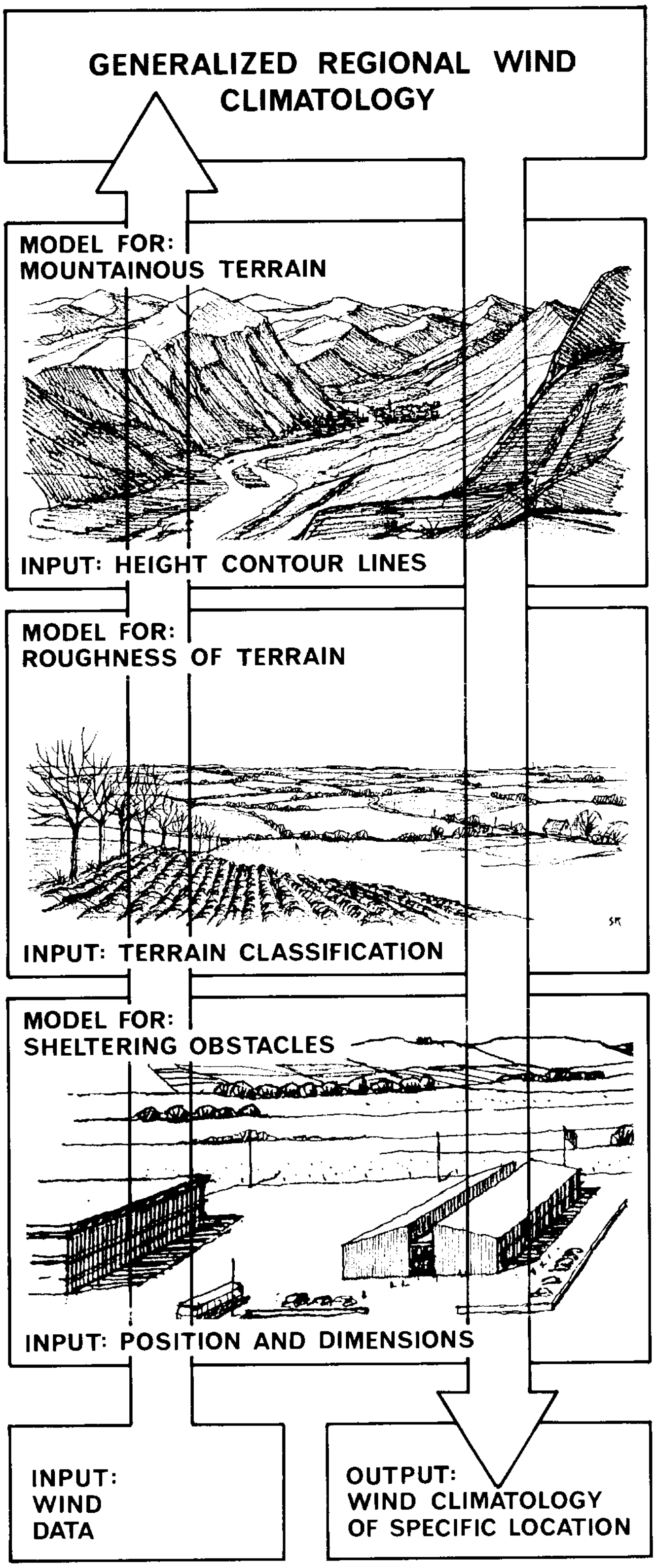


Figure 1. The Wind Atlas methodology used in WAsP. Meteorological models are used to calculate the regional wind climatology from the raw data series. In the reverse process — the application of wind atlas data — the wind climate at any specific site may be calculated from the regional climatology (Troen and Petersen, 1989).

The predictions from WAsP for wind flows over simple isolated hills compare well with the measured data from the two benchmark field measurements of Blasheval (Walmsley *et al*., 1990) and Askervein (Troen, 1990). However, in line with other linearised numerical models, WAsP fails to predict the low flow speeds close to the ground in the lee of Askervein, where some degree of flow separation is suspected. A preliminary comparison between wind tunnel, analytical and numerical (WAsP, BZ model) predictions with field measurements over a 2-D escarpment of about 30 degree slope at Hjardemaal, Denmark, is reported by Jensen *et al*. (1990). Reasonable accuracy was achieved by WAsP, except for the decay rate of the perturbation downstream of the escarpment ridgeline.

Additional independent assessments of WAsP for more complex terrain situations, which lie largely within its operating envelope, generally confirm the reliability of the predictions under these conditions. Holttinen and Peltola (1993) report satisfactory WAsP predictions compared to field data for several sites on the relatively flat, western coast of Finland. Sandström (1994) reports on a field and WAsP comparison from measurements taken at Vårdkasen, a 175-m wooded hill and a reference site on the coast about 5 km away. It was concluded that WAsP simulates the wind field well provided the terrain is not too steep.

2.2 Orographic model

The orographic model used in the WAsP package is of particular importance to this report, which focuses on terrain effects.

The model is similar to the MS3DJH family of models (Walmsley *et al*., 1982), which is also based on the original analytical solution by Jackson and Hunt (1975). Assuming linear equations of motion, the model uses polar representation and a polar zooming grid to create higher resolution of the terrain closest to the site in question. It first calculates the potential flow perturbation induced by the terrain. The potential flow solution is then modified to accommodate, in an approximate sense, the effects of surface friction in the inner-layer close to the surface. A more detailed description is provided in the European Wind Atlas (Troen and Petersen, 1989) and by Troen (1990).

The orographic model is necessarily limited to neutrally-stable wind flows over low, smooth hills with attached flows, in a similar manner to the original analytical model by Jackson and Hunt (1975). Taylor *et al*. (1987) note that this analytical model appears to give reasonably good results on the hilltop and upstream for situations with $h/L \leq 0.4$, depending on the value of L/z_0 (hill height h, hill half-length L, surface roughness length z_0). The corresponding hill slope limit, θ_c, would be somewhat greater than 0.2, depending on the exact shape of the upper half of the hill profile.

A detailed analytical treatment of wind flow over hills is provided by Hunt *et al*. (1988a, 1988b).

2.3 WAsP development

The improvement of the WAsP package and its utilities is an on-going process. However the work reported here utilises WAsP as a commercial package and no attempt has been made to develop program elements such as the orographic model any further. Such improvement will be the subject of future projects. However several current (1995) developments are worth noting here.

The possibility of the wind turning over steep terrain into an adjacent sector confuses the procedure of using a unique speed-up factor in each sector and creates a dilemma for the WAsP model. This has led to the development of the currently experimental Version 4.1, which is physically more appropriate. Whereas WAsP V4.0 first applies the speed-up factor associated with the sector in which the wind is blowing at the reference site and then turns the wind according to the target site terrain, WAsP V4.1 first turns the wind according to the target site terrain and then applies the speed-up factor associated with the resulting and possibly new wind direction sector.

For many instances in the current case studies, it is evident that the direction sector of the predicted flow using V4.1 remains unchanged from V4.0 and initial trials indicate that the results from the two versions are very similar in the cases considered. It is therefore not worth presenting any comparative data from the two predictions here. WAsP V4.1 was used to create the predictions for the case study presented in Section 5.

A further useful modification was made to provide the option of having the sector-wise measured mean wind speeds printed in the raw data histogram (WAsP 4 parameter file, wasp.par, $P_{34} = 1$) and the sector-wise predicted mean wind speeds in the result display (wasp.par, $P_{43} = -1$).

3 Factors affecting the prediction process

The combined WAsP Analysis and Application procedures may be considered as a transfer function model linking the wind speeds at the reference site with those at the predicted site. WAsP assumes that there is a different and unique speed-up ratio between the two sites for each wind direction sector, which is determined by the roughness field, and local orography of the reference and predicted sites. This ratio is independent of wind speed and climatic conditions, which are normally assumed to be neutrally stable.

For a well-behaved transfer-function system, the overall cross-correlation coefficient for mean wind speeds in each sector between two sites must be unity. The correlation for all sectors combined must also be unity. A high correlation between the reference and predicted sites is therefore an essential condition for an accurate prediction by the WAsP model. Evidently, such a condition also applies to the “Measure-Correlate-Predict” (MCP) prediction methods.

3.1 Atmospheric conditions

It is accepted that errors in the prediction due to non-standard atmospheric conditions affecting the behaviour of the wind flow can be very significant. The climatic conditions that cause the transfer function to deviate from the neutrally stable WAsP model may be roughly sorted into the following two categories.

a. The two sites lie in different wind regimes as a result of one or more of the following:

   - excessive horizontal separation relative to the scale of the prevailing weather systems,
   - excessive vertical separation that transcends the interface between high and low altitude wind regimes, or
   - moderate separation but with local strongly stable stratification, inversion layers, sea breezes or density driven flows prevailing.

b. The two sites lie in the same weather regime, but the prevailing atmospheric conditions are not neutrally stable.

The degree to which the prevailing climate departs from the standard, neutrally stable conditions assumed by WAsP will obviously affect the accuracy of prediction for any site, whether or not they lie within the WAsP performance envelope for site terrain. These climate effects could vary from being rather unimportant to having a very extensive influence on the outcome. However, the effects from mildly stable-stratified conditions, such as in the second category, may be corrected for by the inclusion of a stability correction based on the surface heat flux or by user manipulation of the general WAsP parameters for the inversion height (P_6) and the strength (P_7) (see Petersen *et al*., 1996). Both categories would also be responsible for a significant reduction in the cross-correlation of mean wind speeds measured between the two sites, which is a commonly used performance indicator for both WAsP and MCP methods.

Field measurements of wind flow over hilly terrain in non-neutrally stable conditions are not common due to their difficulty and the wide range of possible atmospheric conditions of interest. The effects from the prevailing atmospheric conditions on the flow speed-up can therefore be expected to vary a great deal. For example, while reporting on field measurements over Cooper's ridge, Coppin *et al*. (1994) note that the mean-flow speed-up reduces for unstable flows and increases by up to 100% in stable flow conditions. The assessment of WAsP predictions under strong thermal effects has been reported by Sempreviva *et al*. (1986, 1994) for the hilly terrain of Sardinia.

The individual effects that each type of climate phenomenon has on the WAsP prediction performance are too diverse for proper consideration in this project and should be the topic of a separate investigation.

3.2 Orography

Besides climate, the other most significant category of factors affecting the WAsP prediction performance are those associated with the terrain of both the reference and predicted sites.

Such errors could be influenced by the following factors:

- Individual site ruggedness
- Extensive flow separation
- Topographic features beyond the terrain map considered by WAsP
- Site elevation
- Hill height relative to the boundary-layer height
- Effective surface roughness length due to the ruggedness of terrain
- The degree of turning due to large-scale terrain effects and the resulting changes in the frequencies of occurrence in each sector.

An important issue of the sensitivity of WAsP to map size has been addressed by Landberg and Mortensen (1993), who recommend a minimum area of at least 6 by 6 km^2 depending on site complexity.

Orographic effects are the main focus of this report and are discussed more fully in Section 4.

3.3 Wind speed records

The case study analysed later in Section 5 uses a wind speed averaging time of 10 minutes, which coincides with common usage. In making its prediction, the WAsP model must assume that the 10-minute wind speeds are fully correlated between the two sites and are related by a simple transfer function. However, it is doubtful if a 10-minute wind regime would cover both sites unless they are situated very close to each other. Inevitably, site pairs are mostly separated by a significant distance. For example, the site pairs such as 01-06 of the current case study are up to 50 km apart. A longer averaging time of say, 1 hour, may be more appropriate in these cases to allow a particular wind speed to physically envelope the 2 sites in question. However, only a small improvement is evident in the cross-correlation coefficients with zero time lag for wind speeds averaged over 1 hour rather than over 10 minutes. This issue therefore was not pursued further and remains unresolved. In contrast to cross-correlation estimates, the WAsP Atlas file deals with mean-wind statistics, which should remain unaffected by these spatial effects.

Field observations show that the record length is another crucial factor in the magnitudes of the resulting correlation coefficients. Box and Jenkins (1970) advise that at least 50 data pairs are required to obtain a reliable correlation. Fortunately, wind speed records are normally several orders of magnitude greater; e.g. a one-month record of 10-minute mean wind speeds contains over 4,300 data points. However, observations of wind speed reported later indicate that monthly, seasonal and even yearly variations significantly affect the correlation values. Relatively short-term measurements therefore allow a significant variation in the transfer function, which is determined by the prevailing atmospheric conditions at the time of the measurements.

3.4 Weibull frequency distribution

In order to adapt the measured wind data for the Atlas file, the WAsP Analysis procedure makes use of the standard Weibull frequency distribution as a tool to represent the frequency distribution of wind speed in each direction sector. The generalised wind data are created by forcing the measured data to fit a standard Weibull distribution. However, the measured distributions do not always fit the standard frequency distribution closely. The magnitude of any prediction error must be affected by the degree of transformation necessary during the Analysis procedure to create the Atlas file. The magnitude of this error is manifested in the self-predictions when the reference and predicted sites are the same.

3.5 Wind direction

The direction rose is often divided into 12 equal direction sectors. Steep, oblique ridges affect the direction of the incident flow. This turning may cause the wind direction to fall into an adjacent direction sector, which is different to the current one at the reference site. This problem is addressed in current modifications to the WAsP model described in Section 2.3.

4 Accumulation of orographic prediction errors

It has been shown that the size of any error by WAsP in the prediction of mean wind speeds is predominantly dependent on the degree that the operational limits are violated by factors that are associated with the atmospheric conditions and also the terrain.

Consider here, only the effects from terrain on the accuracy of the WAsP prediction model.

When applied to estimate the mean wind speeds, U_{Pe}, at the predicted site using measured data at the reference site, U_{Rm}, WAsP first creates a generalised Atlas file by means of its Analysis procedure. The Atlas file represents the same distribution of wind speeds and directions for the whole area around the reference site, but with all local obstacles, surface roughness and orographic effects either standardised or removed. The effects from local obstacles, roughness and orography are determined for each direction sector using built-in physical models. The Atlas file is assumed to be universal within a region defined by the extent of the wind regime at the reference site. The predicted site is assumed to lie in the same wind regime so that the same Atlas file may then be used to predict its conditions. The Atlas file generated from measured data at the reference site is then used to estimate the wind speeds and energy at a predicted site, taking into account the local obstacles, surface roughness and orographic effects at the predicted site, using the WAsP Application procedure. The wind atlas methodology of WAsP is shown in Figure 1.

For the purpose of this discussion, consider first the WAsP Application process applied using generalised wind speed data from the Atlas file, U_A, to estimate the sector-wise wind speeds at a particular (predicted) site, U_{Pe}. The accurate speed-up correction for orographic effects has an accompanying error E_2. The error will normally have a positive sign in line with the tendency for WAsP to over-predict rugged sites when using a flat reference site.

Steep terrain promotes flow separation, particularly on the lee side of a ridge lying at an obtuse angle to the wind flow. The extent of the steep terrain within the area of interest surrounding a site is a direct measure of the ruggedness of the site. When the flow is detached from the ground, the effective orography is modified to something that is less rugged than the actual terrain. Surface shear stresses are also modified. If the separated areas are significant in extent over the surrounding terrain, then the flow speeds over more elevated terrain such as a ridge could be expected to be consistently less than if the flow remains attached. Linear numerical models such as WAsP, that assume attached flows, could therefore be expected to consistently over-predict flow speeds over rugged terrain when using a flat site as the source of the reference data.

Supporting evidence for the over-prediction of sites in rugged terrain is available in the literature. Some over-prediction is noted by Sempreviva *et al*. (1986) for Mt. Arci (700 m) near the coast of Sardinia. Despite the strong thermal activity characteristic of this region, high frequencies (46%) of neutral stability induced by strong winds were recorded at Mt. Arci. Sandström (1994) reported on a successful WAsP field comparison at Vårdkasen, and concluded that although the overall mean wind speed was only overestimated by 4%, over-estimations by WAsP of up to 80% in the northerly sectors could be attributed to the steep western and northern slopes of Vårdkasen with slopes of up to 0.48. Over-estimation by WAsP is also reported by Grusell *et al*. (1994) for predictions of the wind power densities over 2 coastal hills in Sweden using data from 2 nearby airport reference sites. However, the hill shapes are not available. During the analysis of data from a network of measuring stations in the Republic of Ireland, Watson (1994) reports the use of WAsP to predict the conditions at 2 hill tops, 15.7 km apart, using each other in turn as the reference site. One hill (code name KAN, 264 m a.s.l.) is within the terrain ruggedness limits for WAsP, while the other (KAG, 121 m a.s.l.) lies outside the limits due to the high cliff 1 km away on the coast side. WAsP over-predicted at the 30-m level for the more rugged hill when using the smoother hill as the reference site (KAN to KAG). Little error occurred at the 10-m level. In contrast, WAsP generally under-predicted when used in the opposite direction for the less rugged hill (KAG to KAN). Evidence of over-prediction is also provided by Bowen and Saba (1995) between several flat to rugged hill site pairs near the coast in New Zealand. Additional supporting evidence from the current case studies is discussed in Section 5.7.

The tendency for over-prediction of rugged sites should hold equally well for the Analysis and Application procedures, bearing in mind that the Atlas file can be considered to represent a virtual reference site, which is flat and featureless. Thus, for the Application procedure,

$$U_A + (\Delta U_2 + E_2) = U_{Pe}$$

Conversely, when (previously) analysing the measured data, U_{Rm}, at the reference site to create the corrected speed in the Atlas file, U_A, a further accurate speed-up correction, ΔU_1, with its associated error, E_1, is involved. This Analysis procedure involves the orographic model in the opposite sense such that,

$$U_{Rm} - (\Delta U_1 + E_1) = U_A$$

The overall prediction process utilises both the Analysis and Application procedures in succession, see Figure 1. Combining both equations to eliminate U_A,

$$(U_{Rm} - \Delta U_1 + \Delta U_2) + (E_2 - E_1) = U_{Pe}$$

The estimated speed at the predicted site, U_{Pe}, is made up of the correct (measured) speed, U_{Pm}, and the overall prediction error, which has accumulated from the two stages of the prediction process. The correct estimation at the predicted site is assumed to involve no errors and is made up of the following,

$$U_{Pm} = U_{Rm} - \Delta U_1 + \Delta U_2$$

$$\therefore U_{Pe} = U_{Pm} + (E_2 - E_1)$$

The overall prediction error in the WAsP prediction process is therefore (E_2 - E_1).

The overall prediction error is shown here to be determined by the difference in the two individual WAsP procedure errors. If errors due to climatic influences are ignored here, both procedure errors are solely due to the terrain at the two sites being processed. Errors due to the orography at the reference site are contained in E_1 and errors due to the predicted site in E_2. The magnitudes of the individual procedure errors depend on the degree that each site contravenes the performance limits of the WAsP prediction model. Both errors as defined, share the same sign because both the reference and predicted sites are invariably more rugged than the featureless site represented by the generalised data in the Atlas file. The sign of the overall prediction error may be positive or negative (signifying over- or under-prediction) depending on the relative magnitudes of the two individual procedure errors. A certain degree of cancellation between the two procedure errors is therefore likely to occur.

The relative sizes of the two procedure errors, which are proportional to the individual site ruggedness, thus determine the accuracy and bias of the overall prediction from the WAsP program.

4.1 Prediction bias and level of accuracy

Although the magnitude of the prediction errors cannot be predicted at this stage using the above results, the likely bias and level of accuracy may be assessed in the manner explained below. The possible accuracy of any proposed prediction may be assessed by considering the orography of the reference and predicted sites, before WAsP is utilised. The following examples are offered to illustrate this approach, assuming that the site pairs have a high correlation between their measured wind speeds.

Gentle terrain

When WAsP is used within its performance limits involving no more than gradual, low hill slopes at both sites, both procedure errors, E_1 and E_2, are small. As the terrain between the reference and predicted sites would also likely be similar in this situation, any application errors would tend to be cancelled out anyway. The accuracy of the WAsP prediction under these circumstances will be high.

Similar sites in rugged terrain

Moving outside the performance limits of WAsP, consider similar sites in rugged terrain where the process errors are significant but similar in magnitude: $E_1 \cong E_2$. The overall prediction should still be accurate, as the two errors would tend to cancel each other out. Such a situation obviously occurs for the self-prediction at any category of site. However, it may also occur for two neighbouring sites in rugged terrain, which have similar orography and orientation. This represents an important application involving the prediction of the wind speeds and energy at adjacent sites along a steep ridge in a wind farm.

From rugged to smooth sites

Consider two largely different sites such as a rugged reference site and a less rugged or flat predicted site. In this situation, the procedure errors are unequal, $E_1 > E_2$, and the overall prediction will be under-estimated with a significant negative error.

From smooth to rugged sites

Conversely, consider a smooth or less rugged reference site and a rugged predicted site. In this situation, the procedure errors are unequal, $E_1 < E_2$, and the prediction will be over-estimated with a significant positive error.

5 Case study

5.1 Background

The intention of the case studies is to utilise existing measured wind speed data of high quality to assess the prediction accuracy of the WAsP program under a variety of topographic situations. It is necessary that the sites be situated in complex terrain with a degree of ruggedness that in some cases could be expected to cause significant errors in prediction. The measured data must be reliable and have been gathered simultaneously over a reasonable period of time extending over several years.

It is fortunate that such data are available from a recently completed project based in northern Portugal. The project entitled “Wind Measurements and Modelling in Complex Terrain” was a multi-partner project supported by the European Commission within the Joule programme. Field measurements in Portugal under this programme commenced in July 1991 and are reported in a number of conference papers, such as Restivo (1991), Restivo and Petersen (1993) and Rodrigues (1994). The first two years of field data were also analysed by Landberg and Mortensen (1993) and Mortensen *et al*. (1993a, b). The data gathering has since continued for a total of 3½ years and the results used in the European Wind Atlas II by Petersen *et al*. (1996). These data sets provide the measured wind speed recordings that are used in the current case study discussed below.

5.2 Site locations and description

The region of interest is set in Northern Portugal just north of latitude 40ºN, on the first coastal range of the mountains, some 50 km SW of the coastal city of Porto.

The total number of sites chosen from the 14 available is limited to 5 hill sites and one on the coastal plain in order to keep the current analysis within practical limits. The relative positions of the sites are shown on the map in Figure 2, where the identifying number for each site has been established in the previous literature.

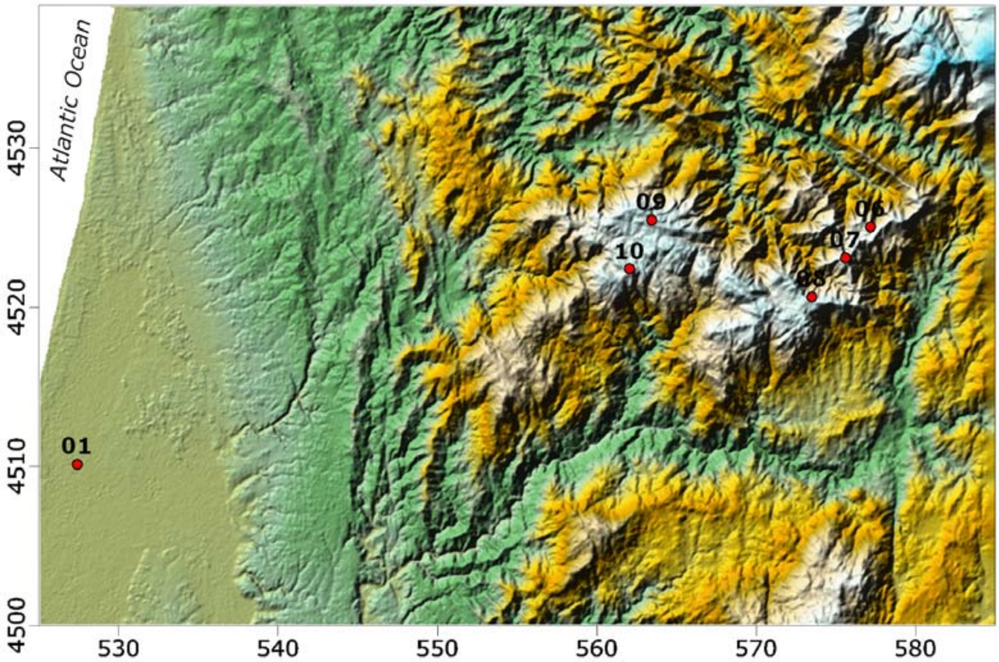


Figure 2 . Overview map showing the field site locations 01, 06, 07, 08, 09 and 10 for the case study. Coordinates are UTM in kilometres (zone 29, WGS 84). The height scale is exaggerated by a factor of four.

The chosen hill sites are in two groups situated on two nearby ridges that overlook the coastal plain and the reference site on the coast. Site 01 is located on the coastal plain, sites 06, 07 and 08 are within about 5 km of each other on a ridge some 45 km away to the east, while sites 09 and 10 are situated on an adjacent ridge about 15 km to their west. The five hill sites have similar elevations between 932 and 1082 m. One site was chosen as the main (predicted) site of interest in each ridge group (sites 07 and 09) and the other sites, 01, 06 and 10 were chosen as potential reference sites. It was considered that the two ridge groups could each represent sites at a typical wind farm with the long-term meteorological station situated at site 01 on the coast, or alternatively, on the wind farm at sites 06 or 10. Predictions between these chosen sites would therefore represent a situation which occurs quite frequently in practice. The surrounding terrain is generally steep with smooth, barren hillsides leading into a number of deep valleys that run down towards the coastal plain. The hill sites are characterised by the same sort of terrain but vary in ruggedness. All the hill sites clearly lie outside the operating limits for terrain specified for the WAsP package.

Details of the chosen sites with their wind statistics and climatologies are taken from the European Wind Atlas II by Petersen *et al*. (1996) and reproduced in the Appendix. Also included are contour maps of the immediate environs at each site, as well as their wind speed frequency distributions and wind direction roses. A detailed description of the sites and their surroundings is also available from Restivo and Petersen (1993).

5.3 Data acquisition

The wind measurements were made at a height of 10 m a.g.l. at each site. Mean wind speeds were measured using Risø 69 cup anemometers, recording consecutive 10-minute averages and 3-s gust speeds. The Aanderaa Instruments 2750 wind vanes recorded the instantaneous wind direction. The data were collected using Aanderaa Instruments 2990 data storage units over a period of about 3½ years from about July 1991 through to April 1995.

5.4 Prevailing weather conditions

The prevailing winds persistently come from the northwest off the sea with easterly winds from the mountains on very few occasions. It is evident that there are several prevailing weather conditions, which would have a significant influence on the atmospheric flows in the area of interest. In particular, the coastal-plain site appears to be frequently in a different wind regime to the hill sites, which are all above the 900 m a.s.l. elevation. The average monthly mean wind speeds presented in Figure 3 remain relatively higher over the summer months at the coastal site 01 in contrast to the hill sites, which have their peak wind speeds during the winter months. A similar elevation effect has been noted by Cherry and Smyth (1985) on high coastal hills in New Zealand and in Sardinia by Sempreviva *et al*. (1994).

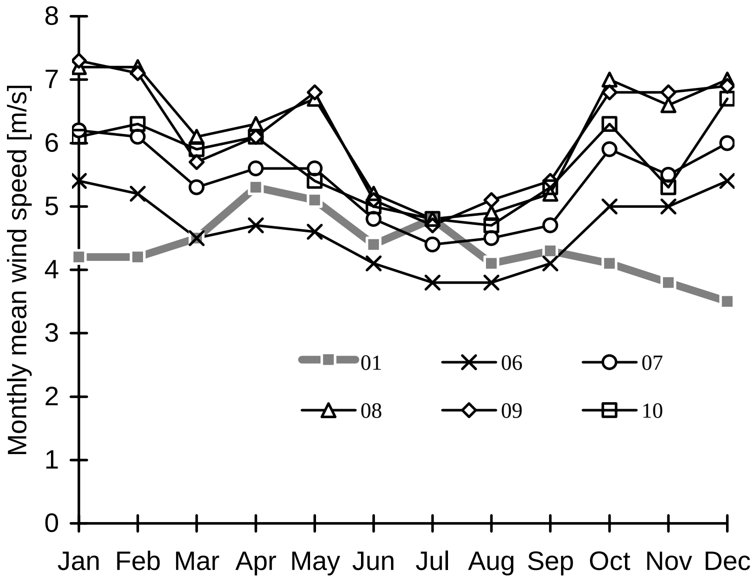


Figure 3. Average monthly mean wind speeds in ms^{-1} from 1991-95 for all selected sites.

During the summer it is evident that regular sea breezes occur which often gain in strength to reach 7 or 8 ms^{-1} in the late afternoons at the coastal site 01. The concurrent time-series traces of wind speed taken at the plains site 01 and the hill site 07 for the typical summer month of August 1991 is presented in Figure 4(a) and clearly illustrates this event. It is evident that although the sea breeze penetrates as far as the ridge-top site on many occasions, little or no positive speed-up of the wind occurs between these two sites under these conditions.

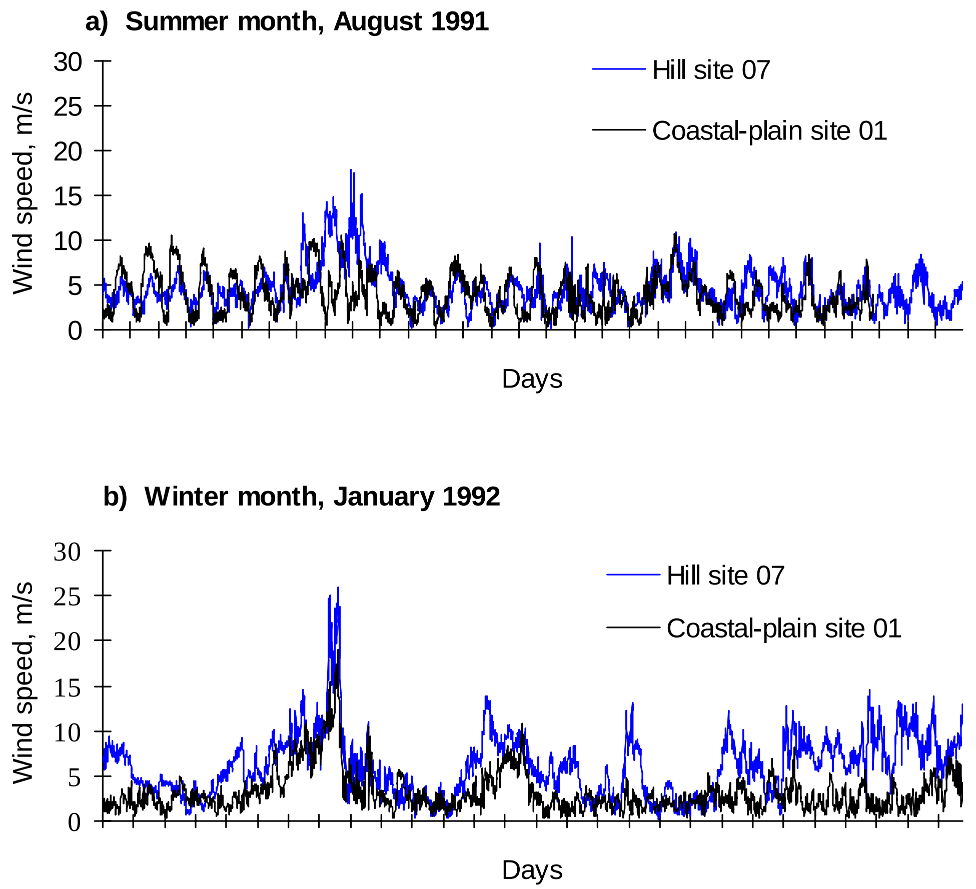


Figure 4. Time-series over one month of wind speed measurements at the coastal plain site 01 and the hill site 07: a) Summer month, b) Winter month.

A similar pair of traces for sites 01-07 is presented in Figure 4(b) for the typical winter month of January 1992. These show the occurrence of frequent winter storms with strong winds occurring at the hilltop site but with significantly weaker winds at the sea-level site. The winter winds mostly back clockwise during the storms and do not remain long in any one sector during the event. It is evident in the examples shown that strong-wind events affect both the coastal-plain and hill sites. However, an occasional storm from the east has been recorded at the hill sites, which is not experienced at the coastal-plain site.

5.5 Measured data

The measured wind speed statistics and climatologies of the 6 sites were generated by the WAsP Analysis procedure and processed by the WAsP Utility Programs package. The data are identical to those presented in the European Wind Atlas II (Petersen *et al.*, 1996). In order to provide a background to the sites of interest, these data have been reproduced from this reference in the Appendix.

The variations of the measured mean wind speeds and speed-up ratios in selected direction sectors between a coastal-plain/hill site pair (01-07) and a hill/hill site pair (06-

07) were investigated further. As the plotting procedures of the spreadsheet Excel limited the analysis to 4,000 measurement pairs, only one representative summer and winter month for each of the 2 site pairs were chosen for analysis.

Figure 5 shows the scatter plots for selected directions of the simultaneous measured mean wind speeds at a) site pairs 01-07 and b) site pairs 06-07 for typical summer and winter months.

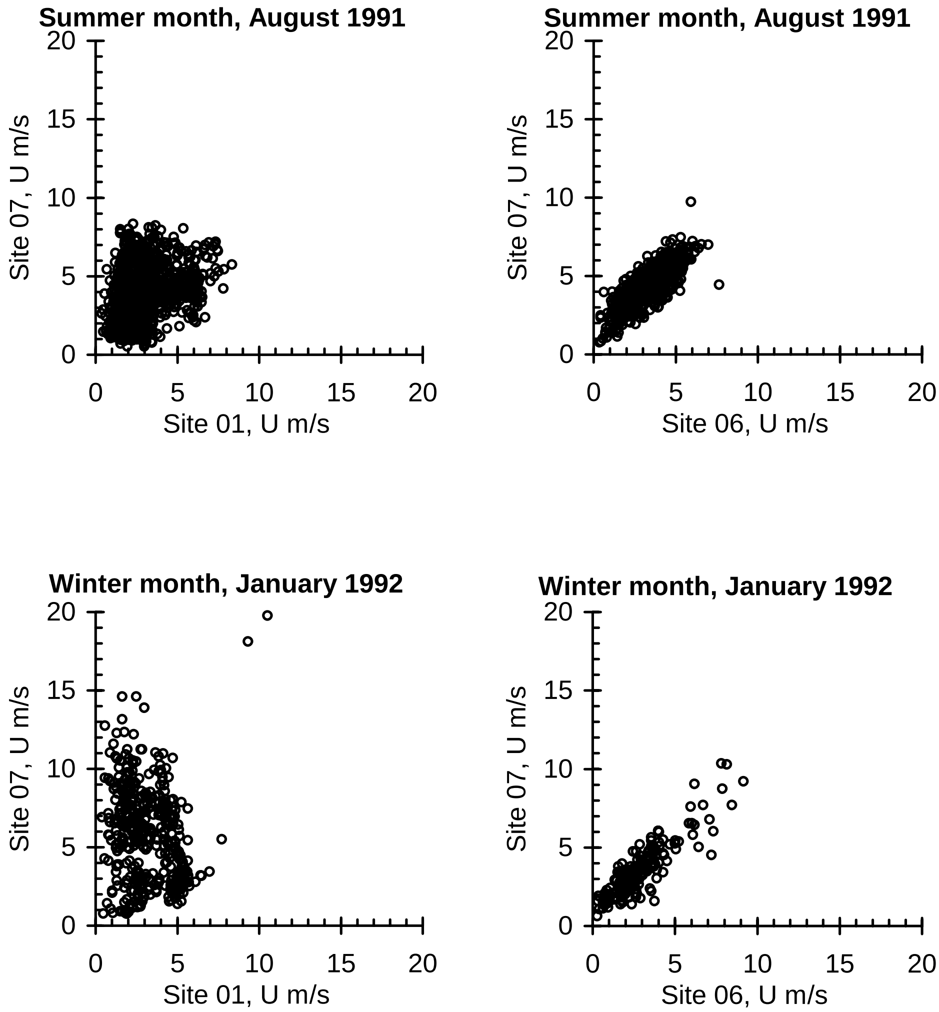


Figure 5. Example of scatter plots of measured wind speeds at sites 01, 06 and 07 for the 330º direction sector in typical summer and winter months for selected site pairs. a) coastal-plain site 01 and hill site 07 (left-hand graphs), b) hill sites 06 and 07 (right-hand graphs).

The data are re-plotted in Figure 6 (a, b) as speed-up ratios against the reference site wind speeds.

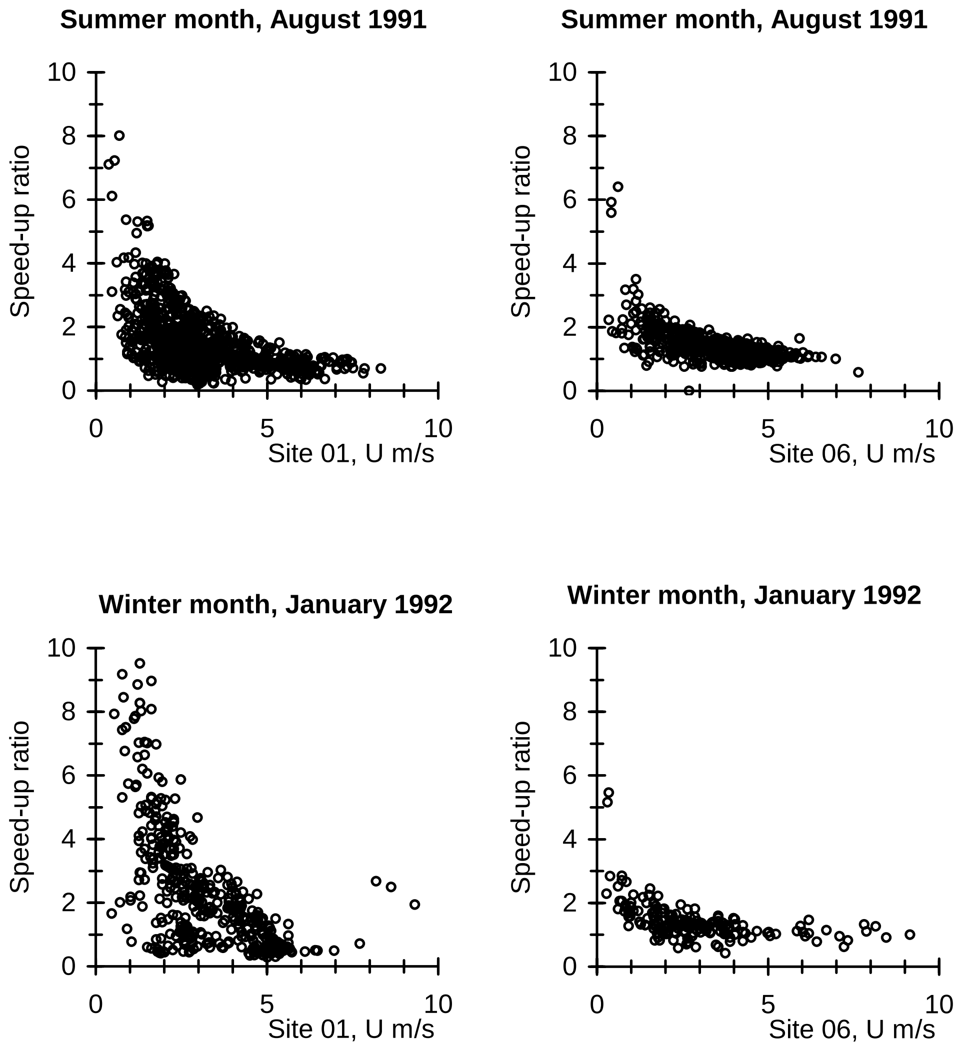


Figure 6. Example of scatter plots to show the effect of mean wind speed at reference sites 01 and 06 on the measured speed-up ratios of at the predicted site 07 using measured wind speeds for a summer and winter month. a) coastal-plain site 01 and hill site 07 (left-hand graphs), b) hill sites 06 and 07 (right-hand graphs).

The unique speed-up ratio for each direction sector expected from a WAsP prediction would be specified by a single sloping, straight line in the scatter plots of Figure 5 and a single horizontal line in the speed-up plots of Figure 6. In contrast, the instantaneous speed-up ratio of the measured wind speeds can be seen to vary widely, especially for the coastal-plain/hill site pair (01-07). Significant variation in the speed-up ratios is also evident between the summer and winter owing, presumably, to the different climatic conditions prevailing during each season. The range of speed-up ratios occurring increases dramatically, sometimes to values exceeding 10, as the reference speed falls below 2 or 3 ms^{-1} (Figure 6). Speed-up values at high wind speeds tend to a unique value close to the long-term average for that sector. An obvious exception is the behaviour for the site pair 01-07 in the 90^o-sector (not shown). The adjacent hill/hill site pair (06-07) exhibits a much better behaved relationship between wind speeds at each site (Figure 5), which tends more closely to a single predicted speed-up value as in WAsP.

Peak speed-up ratios generally occur with winds in sectors that are close to being normal to the ridgeline while minimum ratios occur in sectors that are parallel to the ridgeline. The orientation of the ridgeline to the prevailing wind is therefore an obvious factor in determining the magnitude of the overall speed-up ratio.

5.6 Cross-correlations of measured wind speed

Cross-correlation coefficients of wind speeds at zero time lag for various site pairs were calculated with in-house software using the wind speeds that had been measured throughout the 3½ years of records. A threshold of 3 ms^{-1} was imposed to exclude low wind speeds that are largely ill-defined in direction. The threshold speed was chosen to coincide with the commonly used cut-in speed for wind turbines and does not omit the winds which provide the available wind energy.

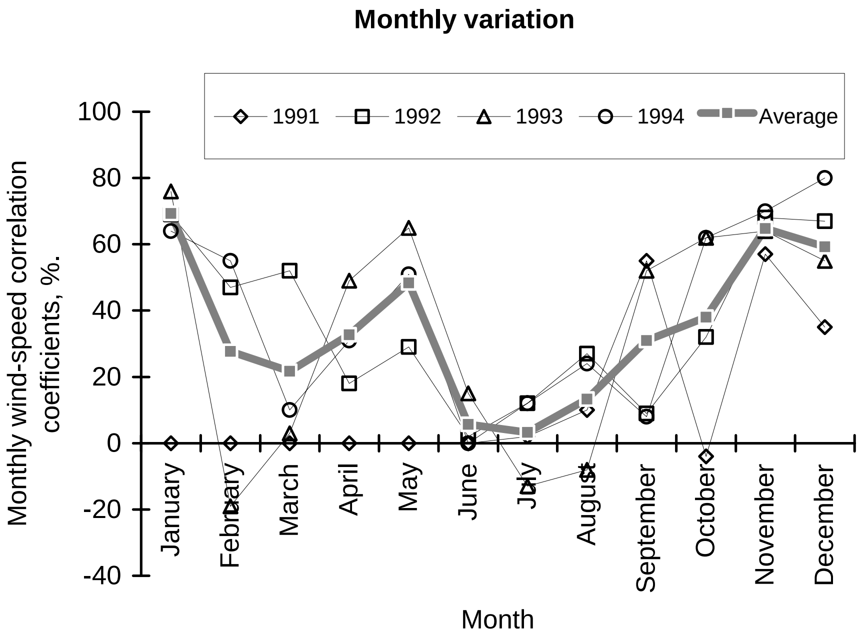
The resulting coefficients using 10-minute mean wind speeds over one-year periods are given in Table 1. It is evident that the correlation coefficients are not particularly high for any site pair and are the lowest for the pairs involving the coastal-plain site 01. All the hill/hill site pairs may be placed in a relatively high-correlation site category (at 60-85%) while all the coastal-plain/hill site pairs fall into a distinctly separate category of relatively low-correlation sites (35-45%).

Table 1. Table of correlation coefficients of 10-minute (above diagonal) and hourly (below diagonal) mean wind speeds taken over one-year periods with zero time lag.

Site		**01**	**06**	**07**	**08**	**09**	**10**
01	1992	100	31	35	40	32	41
	1993	100	38	43	45	42	43
	1994	100	44	46	48	45	42
06	1992	33	100	79	74	71	62
	1993	40	100	77	74	69	61
	1994	46	100	82	77	76	64
07	1992	36	83	100	80	79	65
	1993	45	82	100	79	79	64
	1994	48	86	100	84	85	67
08	1992	42	77	83	100	79	70
	1993	48	78	82	100	81	66
	1994	49	81	86	100	86	67
09	1992	33	75	82	82	100	62
	1993	44	73	82	84	100	64
	1994	46	79	87	88	100	66
10	1992	42	66	69	73	64	100
	1993	45	65	67	69	66	100
	1994	44	67	69	71	67	100

Cross-correlation coefficients calculated from the same wind records but with the wind speeds averaged over 1 hour are also shown in Table 1. It is evident that the longer averaging time only slightly improves the correlations for all the site pairs. It may therefore be concluded that the use of a longer averaging time such as one hour to account for site separation is not effective, as high values of the coefficient could not be achieved for any site pair in this way.

To gauge the effects of seasonal variations, the cross-correlation coefficients were also calculated for each separate month of the 3½ year recording period and also for 3, 6 and 12-month periods. The results are presented in Figure 7 and Figure 8 for the site pairs 01-07 and 06-07, respectively.



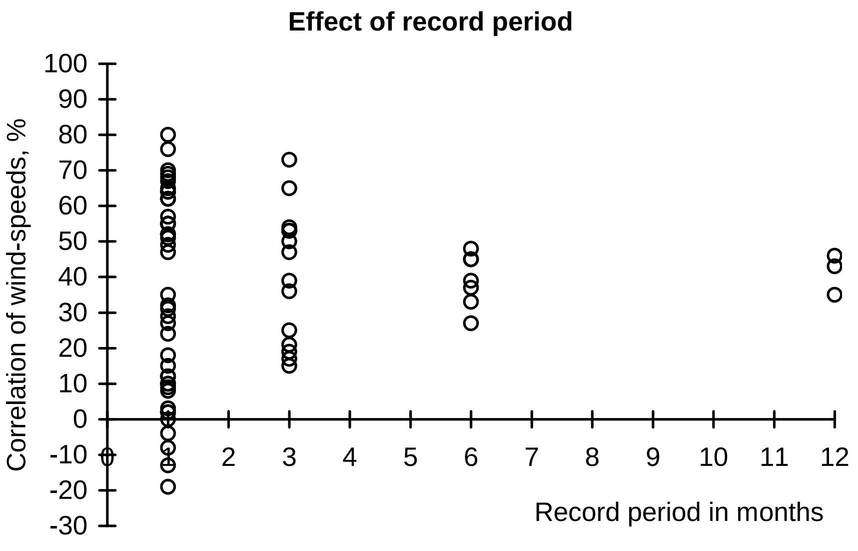
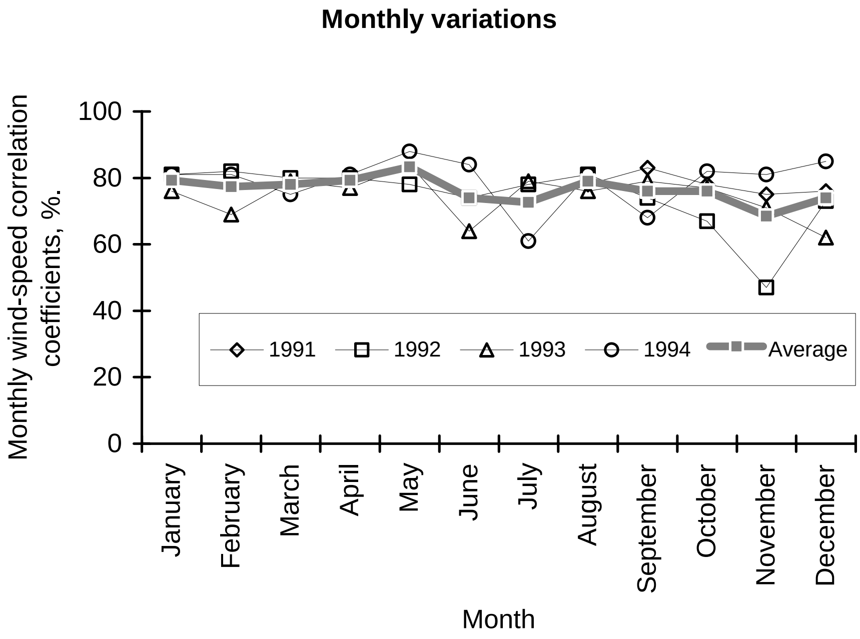


Figure 7. Correlation coefficients between 10-minute mean wind speeds measured at selected sites over various record lengths and months of year, here coastal-plain site 01 and hill site 07.



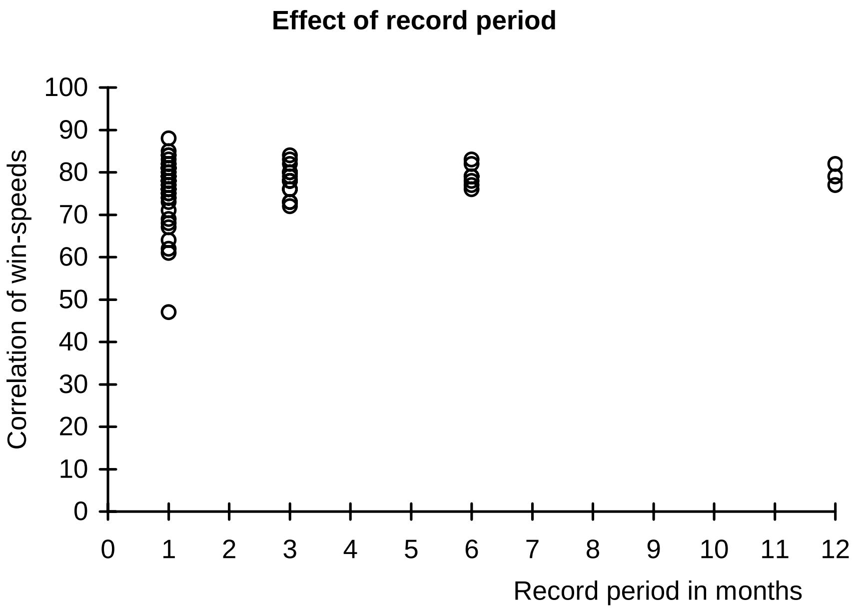


Figure 8. Correlation coefficients between 10-minute mean wind speeds measured at selected sites over various record lengths and months of year, here hill sites 06 and 07.

It is evident that the hill-hill site pair 06-07 is significantly better correlated than the coastal-plain/hill pair (01-07). Monthly correlations for the coastal-plain/hill pair (Figure 7) are best in the winter months and deteriorate markedly during the summer when, presumably, there are stronger thermal effects prevailing. It is also clear that the short-term values of the correlation vary widely from month to month and do not individually provide a clear indication of the true correlation between the sites. Correlation periods of at least one year would be required to provide a reasonable indication of the true correlation between sites in order to account for seasonal variations.

5.7 WAsP predictions

Predictions of the mean wind speeds and wind power densities for all site pairs by WAsP V4.1 are presented in Table 2. All wind speeds are considered without the use of a threshold speed. A uniform surface roughness length of 3 cm is used for all the hill sites. The surface roughness at the coastal-plain site 01 is relatively low and more varied so a separate roughness map was used for this site.

Table 2. Score tables for predictions at selected sites from 3½ years of measured data. Top row contains the reference sites, left-hand column the predicted sites. Upper table: mean wind speeds and mean wind power densities. Lower table: percentage differences between predicted and measured wind speeds and power densities.

Site		01	06	07	08	09	10	Meas.
01	ms^{-1}	4.2	3.4	3.3	4.4	4.5	4.5	4.3
	Wm^{-2}	112	52	53	129	136	126	120
06	ms^{-1}	5.6	4.6	4.4	6.1	6.1	6.4	4.6
	Wm^{-2}	254	137	135	355	333	366	134
07	ms^{-1}	6.5	5.5	5.3	7.3	7.3	7.5	5.4
	Wm^{-2}	387	230	217	627	572	596	214
08	ms^{-1}	6.3	4.8	4.5	6.2	6.4	6.8	6.2
	Wm^{-2}	457	176	181	329	387	467	325
09	ms^{-1}	5.7	4.6	4.4	6	6.1	6.4	6.1
	Wm^{-2}	293	137	144	325	326	380	324
10	ms^{-1}	5.5	4.3	4	5.5	5.5	5.6	5.7
	Wm^{-2}	256	111	90	236	232	227	225

Site		01	06	07	08	09	10	Meas.
01	ms^{-1}	-2	-21	-23	2	5	5	0
	Wm^{-2}	-7	-57	-56	8	13	5	0
06	ms^{-1}	22	0	-4	33	33	39	0
	Wm^{-2}	90	2	1	165	149	173	0
07	ms^{-1}	20	2	-2	35	35	39	0
	Wm^{-2}	81	7	1	193	167	179	0
08	ms^{-1}	2	-23	-27	0	3	10	0
	Wm^{-2}	41	-46	-44	1	19	44	0
09	ms^{-1}	-7	-25	-28	-2	0	5	0
	Wm^{-2}	-10	-58	-56	0	1	17	0
10	ms^{-1}	-4	-25	-30	-4	-4	-2	0
	Wm^{-2}	14	-51	-60	5	3	1	0

Similar predictions were reported by Mortensen *et al*. (1993a) using WAsP V4.0 with 2 years of data. The associated percentage errors of the current predictions when compared to long-term measured data (3½ years) are given in the lower table of Table 2. The errors vary in sign and are sometimes large. However, good predictions are obtained for site pair combinations involving 06-07 and 01-09-10, including all the self-prediction cases. It is important to note here that WAsP consistently over-predicts the mean wind speeds for the hill sites (except 09 and 10) when using the flat 01 site as the reference. Site 10 has a small negative error for the mean wind speed but the wind energy density is over-predicted. Site 09 is the only exception. The cause and behaviour of these prediction errors are discussed elsewhere in this report.

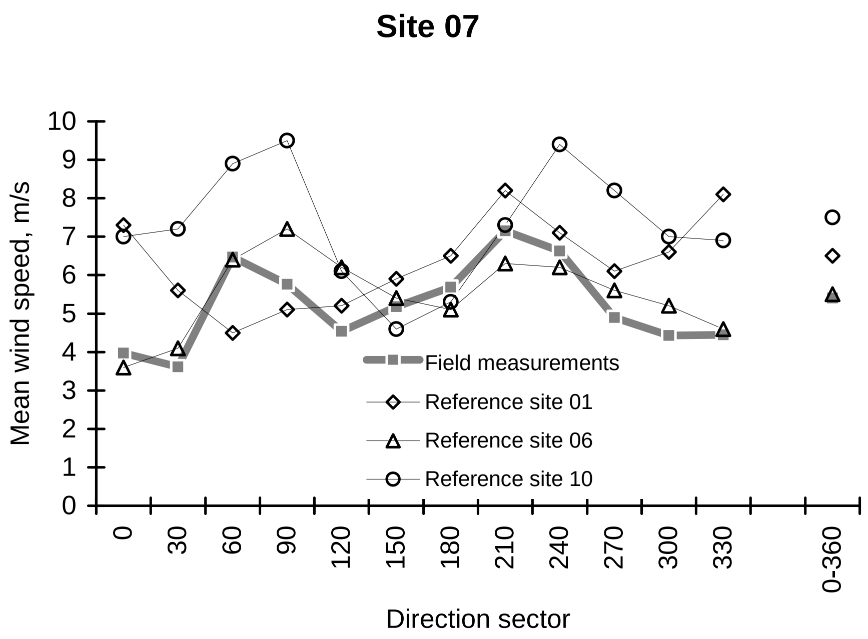
A common procedure when assessing sites for wind energy potential is to list the sites by decreasing wind power density. Lists of the site predictions sorted in this way are given in Table 3 using various reference sites. The lists include the actual measured values and are compared with those from WAsP predictions. The various reference sites used are given along the top row.

Table 3. Tabulated list of sites in order of decreasing wind power density – taken from the measured data and predictions with various reference sites.

Reference site			01		06		07		08		09		10	
Priority	Measured E [Wm^{-2}]		Site number and predicted E [Wm^{-2}]											
1	**08**	325	**08**	457	**07**	230	**07**	217	**07**	627	**07**	572	**07**	596
2	**09**	324	**07**	387	**08**	176	**08**	181	**06**	355	**08**	387	**08**	467
3	**10**	225	**09**	293	**09**	137	**09**	144	**08**	329	**06**	333	**09**	380
4	**07**	214	**10**	256	**06**	137	**06**	135	**09**	325	**09**	326	**06**	366
5	**06**	134	**06**	254	**10**	111	**10**	90	**10**	236	**10**	232	**10**	227
6	**01**	120	**01**	112	**01**	52	**01**	53	**01**	129	**01**	136	**01**	126

Some significant discrepancies in the order are evident depending on the reference site used, due to the different prediction errors incurred between each site pair. WAsP prediction errors for each direction sector are plotted in Figure 9 and Figure 10 for the predicted sites 07 and 09, respectively, using various reference sites: 01, 06 and 10. The measured data are also plotted.

Sector-wise prediction errors are large and for some sectors, often exceed that for all-directions, (given at the RHS of the *x*-axis, 0-360º). Measured sector-wise speed-up factors at all hill sites exhibit similar trends to those examples shown in Figure 9 and Figure 10. Maximum over-prediction errors occur in most cases for the northerly sectors, which coincide with the prevailing wind direction. Maximum under-prediction errors occur for most hill-hill site pairs in the 60º-90º sectors due to the unusually high speed-up factors measured in these directions. The best predictions are between adjacent hill sites 06-07 and to a lesser extent, sites 10-09. Relatively good agreement is also evident between sites 06-09.



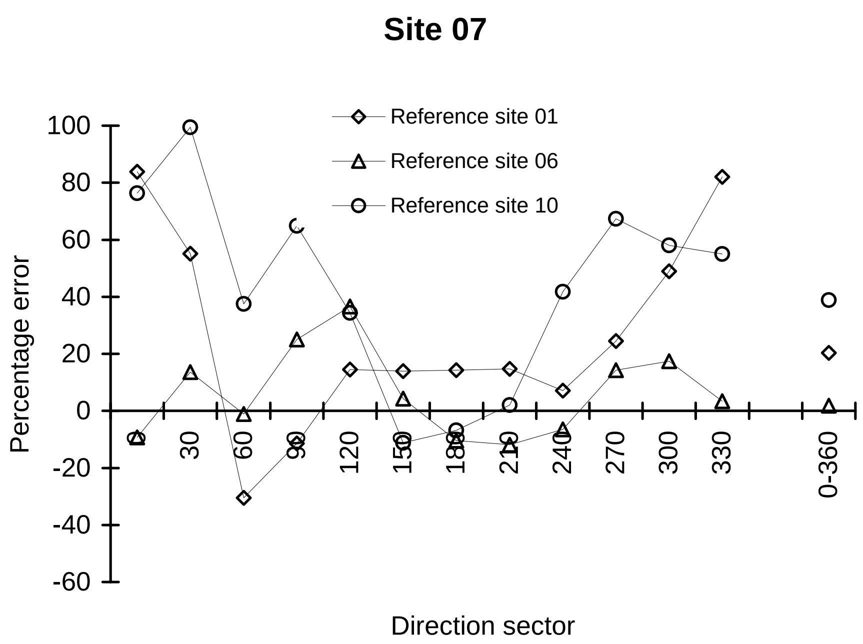


Figure 9. Comparison of measured and predicted data by sector for site 07: a) Mean wind speeds (upper graph), b) Percentage errors (lower graph).

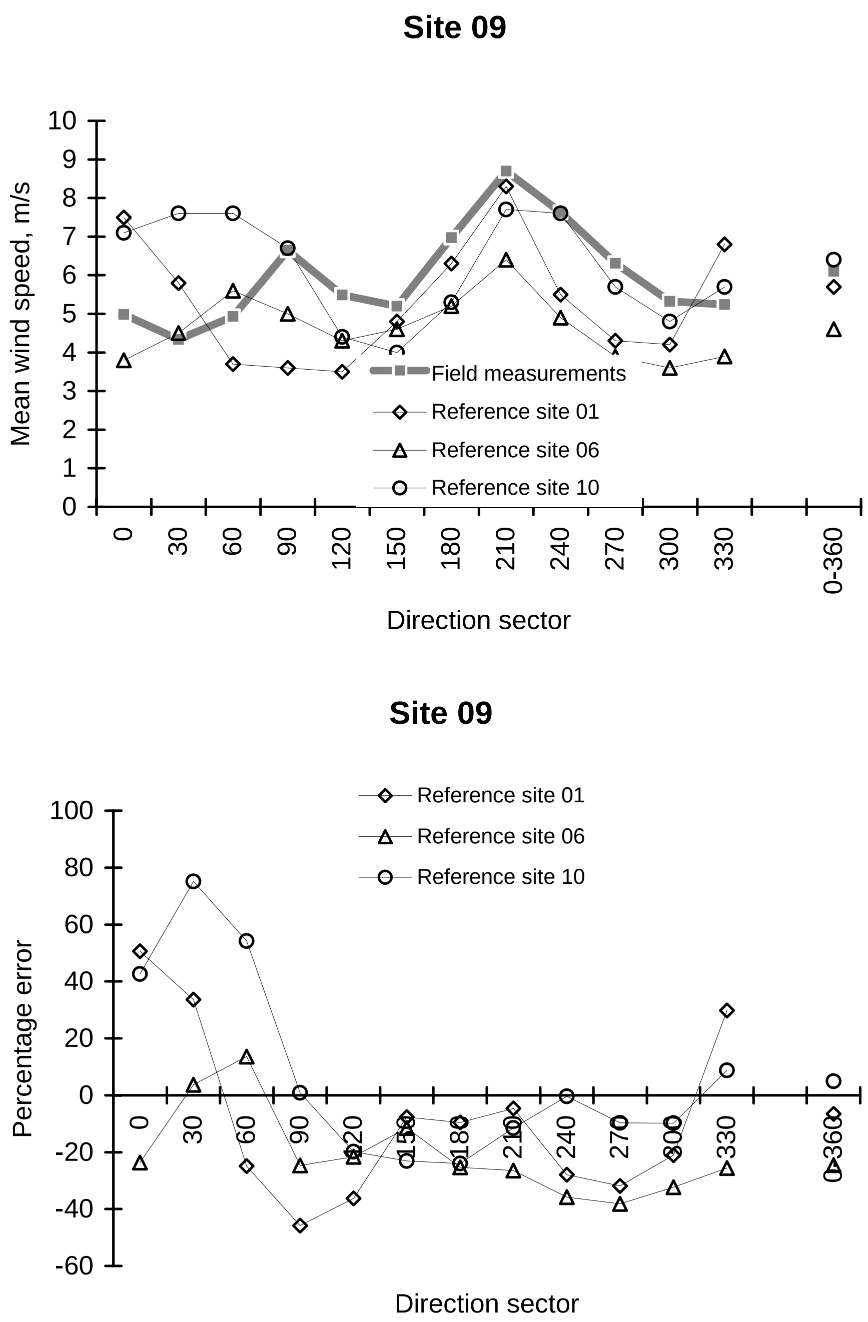


Figure 10. Comparison of measured and predicted data by sector for site 09. a) Mean wind speeds (upper graph), b) Percentage errors (lower graph).

6 Performance indicators

The error associated with the WAsP prediction of the wind speed at a predicted site has been shown in Section 4 to be made up of two separate procedure errors. These are generated as the WAsP Analysis procedure works from the reference site to the Atlas file and then via the Application procedure back from the Atlas file to the predicted site. The magnitude of the procedure errors have been shown in Section 3 to be determined predominantly by both climatic effects and the ruggedness of terrain around the reference and predicted sites. It is finally concluded in Section 4 that the sign and magnitude of that part of the overall prediction error, which is attributable to orographic effects, are determined by the difference between the two procedure errors.

This discussion concentrates on the quantitative effects of site terrain on the performance of the prediction process.

6.1 Wind speed correlations

The cross-correlation coefficient taken from measured time-series data of wind speeds at both sites is often used in the literature as an obvious measure of the site's suitability for prediction techniques such as WAsP and Measure-Correlate-Predict (MCP). A high level of cross-correlation in wind speed will ensure that both sites lie within the same weather regime. However, although it is clear that some atmospheric conditions would be responsible for low levels of correlation, there is no evidence that a high correlation ensures the presence of prevailing neutrally stable conditions. This issue is discussed further in Section 6.2. For sites that lie within the WAsP performance envelope for both terrain and atmospheric stability, a high level of correlation is the only essential pre-requisite for accurate predictions by WAsP (see Section 3).

All the hill sites considered in the present case study are close to the same elevation and exhibit some significant level of correlation with each other (see Section 5). However, the magnitude of the cross-correlation coefficient necessary to indicate that two sites are well correlated is not at all clear from the literature or from the data considered here. It is inferred from the level of correlation obtained here (60-85%), that all the hill sites lie predominantly within the same weather regime. Despite this, the prediction errors for these (moderately well?) correlated hill sites are still large. The plot in Figure 11 of the prediction error and annual average cross-correlation coefficients indicates that WAsP errors can still be substantial for site pairs in rugged terrain, even with correlations above 80% (e.g.: site pair 09-07).

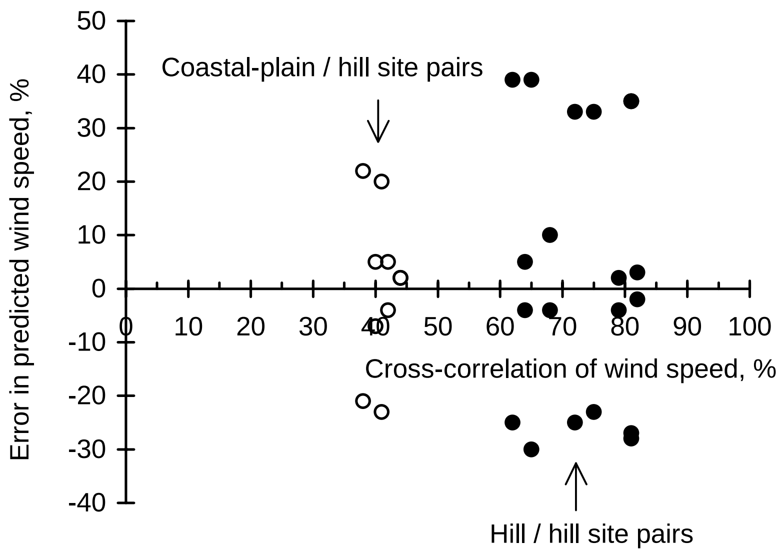


Figure 11. Comparison of predicted wind speeds and the average annual cross-correlation coefficients using measured 10-minute mean wind speeds.

There appears to be no relationship between the size of the prediction error and the cross-correlation coefficient for any of the sites represented in Figure 11. Furthermore, the cross-correlation coefficient is unable to indicate the sign of the prediction error. It can only be assumed that these large prediction errors are also affected by the fundamental limitations of the orographic model when applied to the rugged sites considered here.

In contrast, the low-level plains site exhibits somewhat lower cross-correlation coefficients with the hill sites (35-45%) due, presumably, to more prevalent climatic effects. This situation would be contributed to by the extensive periods of sea breezes, which do not penetrate to the hill sites, and to the strong winter winds at higher elevations and that do not fully reach the low level site on the coast. Such uncorrelated conditions would create a wide range of speed-up ratios between the coast and any hill site, which is confirmed by the field measurements discussed in Section 5.

Correlation coefficients between site pairs are reported by Landberg and Mortensen (1993a) to fall away rapidly for increasing time lag. There is an inherent difficulty in choosing a suitable time lag to account for the separation between sites as the value changes with both wind speed and direction. The time lag between the two functions has therefore been taken as zero in the work reported here.

As a result of the evidence from the current case studies discussed here, it is concluded that the magnitude of the cross-correlation coefficient of mean wind speeds only indicates the extent that two sites share the same wind regime. It does not confirm prevailing neutrally stable conditions and additional information is required to cope with the effects of atmospheric stability on any prediction. A high level of cross-correlation is therefore, not by itself, a good indication of the potential for WAsP to make an accurate prediction. An additional orographic performance indicator is also needed for sites situated in rugged terrain.

6.2 Site ruggedness

It is evident from the above discussion that the individual procedure errors in the prediction process can be high, even for reasonably well-correlated sites. This situation would occur if the terrain of either the reference and/or the predicted site were rugged. Large procedure errors must be expected for sites, which violate the assumptions of the orographic model and therefore lie outside the performance envelope of the WAsP program.

With climatic effects now put to one side and assuming 100% correlation between sites, the remaining procedure errors can now be expected to be predominately determined by the nature of the orography at each site. A practical site parameter is therefore required which quantifies the extent that the terrain at a particular site exceeds the limits implied in the derivation of the orographic model. This could take the form of an orographic indicator, which would be used, with consideration of the cross-correlation coefficient and the prevailing atmospheric conditions, to assess the likely accuracy of a proposed WAsP prediction. A practical consideration is that the indicator should, if possible, be derived directly from the site contour data.

The limitations of the WAsP orographic model have been briefly discussed in Section 2. A proposal for a practical performance indicator is subsequently developed which is based on a number of assumptions that may be summarised as:

- The overall prediction error is equal to the difference between the individual WAsP Application and Analysis errors.
- These two errors are heavily dependent on the degree of flow separation at the site in question.
- The degree of flow separation is dependent on the site ruggedness.
- A possible performance indicator would therefore be the difference between the site ruggedness of the Predicted and Reference sites.

The problem remains how to quantify the ruggedness of a particular site by a ruggedness index using information that is easily available from a contour map. After trying several parameters that are already easily available from the existing analysis, the development of a more suitable ruggedness index will be described.

6.2.1 WAsP speed-up ratio

The actual speed-up ratio for all wind directions as predicted by WAsP between two sites should give some indication of the difference in magnitudes of the orographic effects between the reference and predicted sites. Despite the fact that this factor already contains the WAsP procedure errors, it might serve as a primitive orographic indicator. However it is evident from Figure 12 that there is only a weak relationship between the prediction error and the magnitude of the predicted speed-up ratio. The wide vertical spread in prediction error for all values of speed-up ratio is too large for this parameter to be used as an orographic performance indicator.

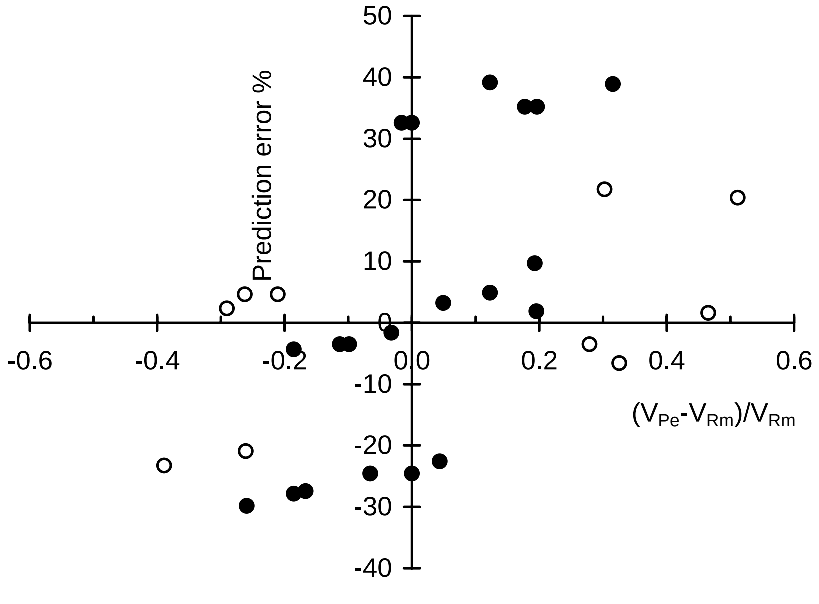


Figure 12. Comparison of prediction errors and predicted fractional speed-up ratios. Circles: coastal-plain/hill site pairs; dots: hill/hill site pairs.

Consideration of only the wind flow in the sector encompassing the prevailing wind may be an effective approximation that would help to improve the indicator just considered. The orographic factors used by WAsP in the direction sector containing the prevailing wind were found for both the reference and predicted sites. In a similar approach as before, each factor could be considered an indication of the magnitude of the WAsP procedure error. The differences in these factors should then provide some indication of the sign and magnitude of the prediction error. However, as before, only a weak relationship was found which remains inadequate to serve as an orographic indicator.

6.2.2 Relative relief

The difference in elevation between the lowest and highest level within a defined map area is termed the Relative Relief, Δz. The European Wind Atlas uses three categories estimated from a 100-km^2 area to categorise the terrain in terms of complexity. The Relative Relief is displayed as a background shading to the resource maps according to the following distribution; none 0-200 m, light 200-800 m and dark >800 m. This index is tabled in Table 4 and plotted against the WAsP prediction error in Figure 13.

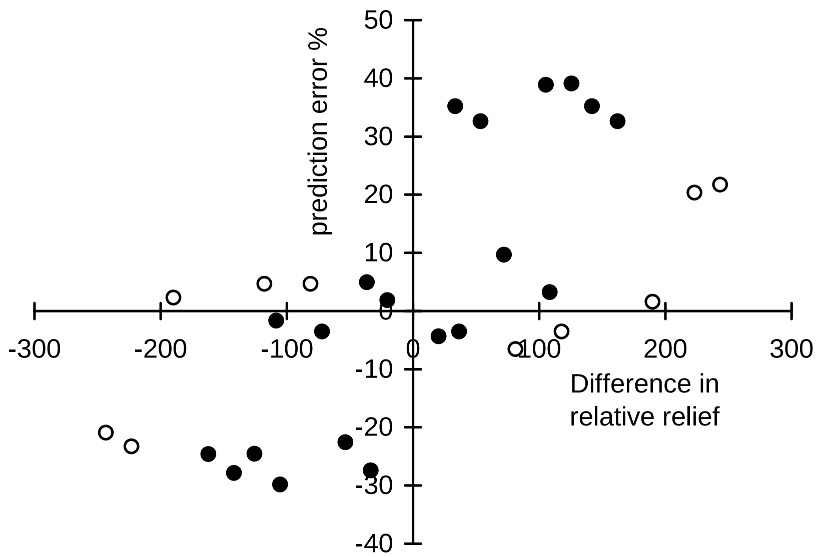


Figure 13. The variation of prediction error with difference in relative relief. Circles: coastal-plain/hill site pairs; dots: hill/hill site pairs.

6.2.3 Standard deviation of terrain height

A preliminary attempt to categorise site ruggedness was first reported by Mortensen *et al*. (1993a). The Portuguese hill sites, which are also the subject of case studies in this report, were sorted satisfactorily into three categories of ruggedness. The index used was the standard deviation of the grid-point heights (σ_z), taken within unit areas of 1 km^2 around each site. The contour heights were first converted to spot heights on a 10-m orthogonal grid pattern and then the standard deviation of the spot heights was calculated. Wider areas such as the 8-km^2 maps, normally used for the WAsP analysis, were found to be less discerning. However it is clear that this parameter is not a true measure of the ruggedness or steepness of a site. Despite this, its relevance will now be explored further using data from the current case studies. The values of the indicator (σ_z) derived for all sites are tabled in Table 4.

Table 4. Table of various terrain ruggedness indices.

Site	Δz	σ_z	% steep terrain	Site category
01	2.9	0.23	0	1
10	120.7	21.2	5.55	2
09	84.2	20.2	8.61	2
08	192.7	42.8	11.48	
07	226.1	42.9	19.68	3
06	246.3	41.6	19.76	3
Askervein	107.0	31.1		
Blasheval	106.7	26.4		

The benchmark sites of Blasheval (Mason and King 1985) and Askervein Hill (Taylor and Teunissen, 1987 and Salmon *et al.*, 1988) have also been included inTable 4 for comparison. Good predictions using WAsP have been reported for both these two hills (Troen and Petersen, 1989) for windward and ridge-top sites. Predictions over Askervein Hill do however fail to predict accurately the low speeds measured in the lee of the hill. This provides an indication that the Askervein terrain might lie just outside the accurate limit for WAsP. In this case, h/L = 0.54 for flows normal to the ridge.

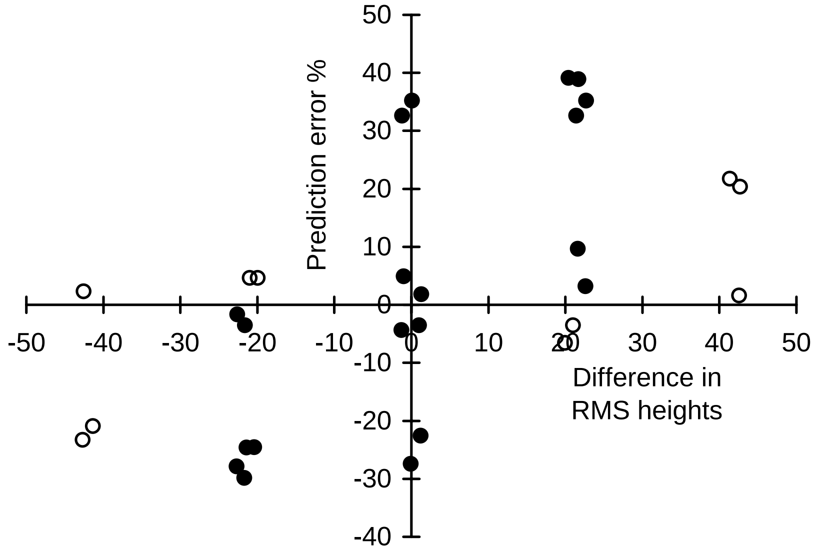


Figure 14. The variation of prediction error with difference in RMS heights.

The WAsP prediction error for each site pair is plotted in Figure 14 against the difference in the site RMS terrain height for the predicted and reference sites. Site ruggedness indices inTable 4 clearly group themselves along the *x*-axis by whether or not the reference and predicted sites are in the same or different ruggedness categories. The relationship between error and index in Figure 14 serves to indicate, albeit rather weakly, the magnitude and sign of the orographic prediction error for a particular site pair. It is evident that the more uncorrelated site pairs containing the coastal-plain site 01 tend to lie on the outer limits of the envelope.

6.2.4 Flow separation

The ability to predict whether or not the flow will separate is an important step in estimating the performance of the orographic model and other linear numerical models which assume the presence of attached flows. The presence of flow separation over a hill is determined by the local surface shear stress tending to zero or by an abrupt edge in the terrain lying across the flow. The presence of flow separation affects the vorticity field throughout the flow. The flow is perturbed by an effective hill shape that is modified by the presence of the separation volumes, which lift the near-surface streamlines away from the surface. The effective hill shape would normally appear to be less steep than the real hill because the separation volumes would lie in the windward and leeward sides of the hill rather than above the ridge. Separation could reduce the effective shape of a steep ridge to that more like an escarpment, with a dramatic reduction in the fractional speed up ratio to one half the value at the crest of the same ridge in attached flow (Britter, 1982).

It is generally accepted (Wood, 1995) that the onset of flow separation depends on the maximum slope of the hill exceeding some critical value, θ_c say, which depends on the surface roughness length and the exact shape of the hill. Wood (1995) reports on the derivation and justification of a practical estimate of the critical slope for flow separation over 2-D hills. This is offered as a means to define a terrain limit, for the reliable operation of linear prediction models such as WAsP, by comparing the estimated critical slope with the maximum slope of the hill surface. If the maximum hill slope is greater than the critical estimated value then any prediction of the flow could be expected to be unreliable. Although this comparison indicates the likelihood of an error, it is insufficient in providing a measure of its magnitude.

The estimate for the critical slope is developed using 2-D sinusoidal-shaped hills, which are demonstrated empirically to indicate the onset of separation successfully for more realistically shaped 3-D hills. The critical slope, θ_c, is given as a function of l/z_0 and h/z_0,

$$\theta_c \cong \frac{\log^2\left(\frac{l}{z_0}\right)}{\left(\log^2\left(\frac{h_m}{z_0}\right)\right)\cdot\left(1+4.2\log^{-1}\left(\frac{l}{z_0}\right)\right)}$$

Wood (1995) specifies the depth of the inner layer, l, through the following implicit equation:

$$l\cdot\left(\frac{U_0(l)}{ku_*}\right)\approx \tfrac{1}{2}k^2\lambda$$

where λ is the base length (wavelength) of the hill, k is von Kármán’s constant, and u_* is the upstream friction velocity.

The height scale h_m represents the height below which the shear in the upstream profile is important to the dynamics of the perturbations to the mean flow and is obtained from,

$$h_m\cdot\left(\frac{U_0(h_m)}{ku_*}\right)^{1/2}\approx \tfrac{1}{4}\lambda$$

Wood (1995) notes that both l/z_0 and h_m/z_0 are functions only of λ/z_0, suggesting that θ_c is also only a function of λ/z_0. Estimates of the maximum slope θ_c of various hills, at which observational experiments have been carried out, were therefore plotted against λ/z_0 (Wood, 1995); the hills and some characteristics are given in Table 5. Wood also plotted the analytical estimate for θ_c, which fits in quite well with observations of the wind flows during the various hill tests reported. The assumption of equal values of θ_c for both the upstream and downstream slopes is implied in Wood's analysis. A note of caution is added by Wood that the 2-D estimate would represent a lower bound to the actual critical slope for separation over 3-D hills and would become less accurate for hills with strong stream-wise asymmetry.

Table 5. Critical hill slopes and other characteristics of field observations analysed by Wood (1995).

Hill	Peak slope	z_0 [m]	λ [m]	Separation
Askervein	~0.39	0.030	800	No
Blasheval	~0.45	0.010	~800	Yes
Brent Knoll	~0.36	0.020	~1200	No
Kettles Hill	~0.18	0.010	2400	No
Llanthony	~0.32	0.500	2620	Yes
Nyland	0.45	0.050	~500	Yes
Sirhowy	0.62	0.003	~2000	Yes

Despite the limitations of this analytical estimate, the complex dependency of the critical slope for separation on the exact shape of the hill has been removed. It thus provides a promising way to determine the value of θ_c for a certain hill and wind direction. Several problems still remain however, particularly in the choice of a representative value for the hill base-length, λ, for sites in complex terrain. In most situations in complex terrain, it is not at all clear which scale of terrain should be considered for this purpose. The simplest solution to this problem is to sidestep the issue by assuming that the critical slope has a fixed, conservative value for all hills. The information provided in Table 5 indicates that such a reasonable limit could be taken as $\theta_c = 0.3$; about 17º, see also Section 2.2.

A further important step would be to estimate the magnitude of the effect that separation would have on the flow by estimating its extent over the surrounding terrain. A rough indication of the extent of the likely flow separation would be the fraction of the terrain, which contains slopes that exceed a chosen critical value.

6.3 An orographic performance indicator

The above discussion leads to the proposed *site ruggedness index*, which is defined by the percentage fraction of the terrain along the prevailing wind direction, which is over a critical slope of 0.3. The definition of the *orographic performance indicator* then follows as the difference in these percentage fractions between the predicted and reference sites.

This option was investigated using the case-study data. The 8×8 km^2 maps are used in these estimates as the 1×1 km^2 maps contain insufficient information on the overall terrain and produce meaningless estimates in contrast to those from the larger maps. The percentage fractions were estimated using a sub-routine, which considers the slopes along the centre radius of each of the 12 sectors. The polar-grid layout is shown in Figure 15 and the values obtained for the ruggedness index are tabulated in Table 4.

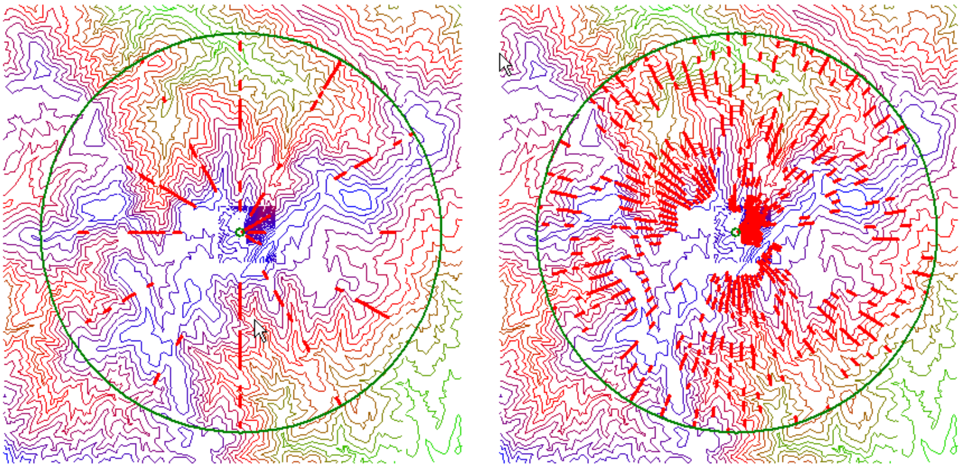


Figure 15. Polar grid overlay to contour map to estimate the site ruggedness index. Left: slopes along the centre radius of each of the 12 sectors; slopes larger than 0.3 are indicated. Right: similar plot, but for 72 sectors.

This performance indicator provides encouraging results when it is plotted against the WAsP prediction errors in Figure 16. The plots representing the hill-hill site pairs lie quite close to a straight trend-line. However, those involving the flat coastal site 01 are marginalized. The systematic trend for the hill-hill site pairs confirms the strong influence of such an orographic indicator in determining the prediction error.

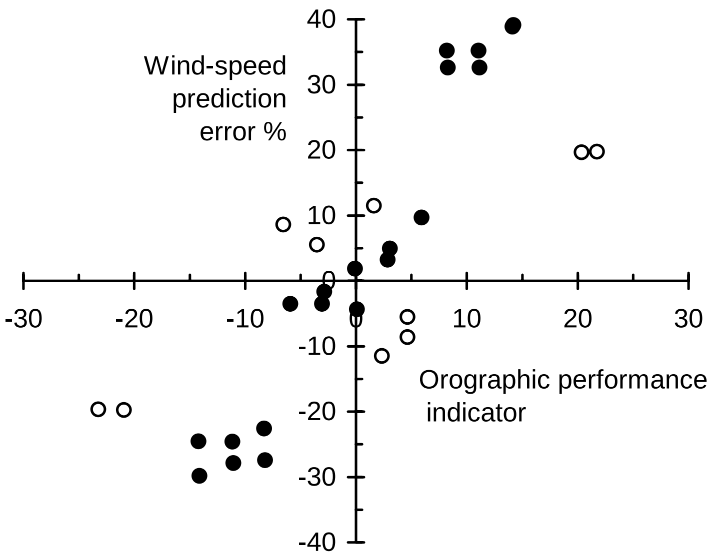


Figure 16. Plot of prediction error and the performance indicator derived from the extent of steep slopes at each site. Circles: coastal-plain/hill site pairs; dots: hill/hill site pairs.

Trend lines may be fitted to the hill-hill site pairs in Figure 16, as a straight line in each quadrant in view of the approximate nature of this indicator, I, e.g.:

$$E = \alpha \cdot I \qquad \text{where} \quad \alpha = 3.3 \text{ for } I > 0 \quad \text{and} \quad \alpha = 2.3 \text{ for } I < 0.$$

The zero crossings of the two trend lines could be shifted apart (to about ±4% in Figure 16) to indicate the operating envelope of WAsP for accurate predictions. However, further reliable field data are required to confirm this.

It is evident from the tabulated site ruggedness indices inTable 4 that the Portuguese sites used for the case studies fall into 3 distinct categories determined by their rugged-ness. Site 08 falls somewhere between category 2 and 3. It can be expected that the differences in site ruggedness between each site pair would also fall into 3 categories and this behaviour is evident in the distribution of the plotted data in Figure 16.

It may be advantageous to distinguish between terrain that is steep, but fragmented such as in a relatively flat, saw-toothed profile, and that which is linked closely together forming one large steep hill. This can be done by altering the grid size in the subroutine for the estimation of the roughness indicator. However, these refinements were tried but the plot distribution in Figure 16 was not altered significantly from the one shown that is produced using a 250-m grid size.

6.4 Discussion

The vertical distribution of the data points about the trend line in Figure 16 is clearly not determined by the level of correlation between the site pairs. The scatter amongst the hill-hill pairs about the trend line appears to be random and could instead be due to variations in the accuracy of the orographic model at each site. In contrast, all the site pairs involving the flat, low level site 01 lie outside the envelope containing the hill-hill site pairs and show consistently smaller prediction errors for all values of the orographic performance indicator. The relatively low correlations of wind speed measured between these flat-hill site pairs (~40%), together with the observations discussed earlier in Section 5.4, suggest that different atmospheric conditions occur between them more often than between the hill-hill site pairs which are at similar elevations. Such conditions could be produced by prevailing stable atmospheric conditions within the elevation range separating the flat coastal site 01 and the other hill sites. Stable stratification has been observed (Coppin *et al*., 1994) to increase any speed-up over a hill by up to a factor of 2 (unless complete blocking occurs). Barthelmie *et al*. (1996a,b) indicate that WAsP would also overpredict wind speeds in the near coastal offshore zone because of predominantly stable conditions. In contrast, unstable conditions tend to reduce the speed-up by small amounts. Stable stratification could therefore be responsible for the reduction of the prediction error that is evident in Figure 16 for the flat-hill site pairs for all values of the orographic performance indicator. Such conditions might be possible if the sea breezes off the cold Atlantic are strong and occur under cloud cover but this has not been confirmed.

It is proposed here that the magnitude of the prediction error for a certain value of the indicator is influenced by the prevailing atmospheric conditions between each site pair. Unstable conditions are likely to increase the error by a small amount while stable conditions would reduce the error by a relatively large amount. Extreme conditions of prevailing atmospheric stability would therefore lie near the outer edge of the envelope of data points. The trend line itself would represent the predominant atmospheric condition common to all the hill sites. This is likely to be slightly unstable because of frequent solar warming of the hill slopes throughout the whole year. However, because of the small effect on speed-up expected from unstable conditions, the trend line may be close to representing neutrally stable conditions.

There is no direct link evident between the atmospheric stability and the level of correlation between sites in this case study or in the literature. However the level of correlation is expected to drop as the atmospheric conditions at a particular site depart from the neutrally stable case. The level of correlation therefore does not provide an indication of the accuracy of any prediction. Neither does it indicate the sign of the error, nor whether it could be expected to lie above or below the trend line. A high level of correlation between the reference and predicted sites does however, remain an essential prerequisite for an accurate prediction.

It is conceded that the estimation of the extent of flow separation would also depend on the place where it is initiated and the terrain downwind on which the flow may re-attach. If separation occurs in a valley area, the flow would probably reattach relatively early on the rising ground on the other side of the valley. Under these circumstances especially if situated well downwind of the site, the separation may only cause a relatively minor alteration to the flow over a nearby ridge unless the whole valley lies within the separated area. If the separation is initiated downwind but close to a ridge, then the flow is more likely to remain detached for longer as the ground falls away in the lee of the ridge and its affect on the ridge flow could be relatively large. Of course, if the site of interest lies within a separated area then any predictions will be meaningless. A practical measure of the above effects is far more difficult than just measuring the extent of the steep slopes. Some judgement could be made when identifying the steep slopes by eye, but it is preferred that any indicator should eventually be obtained in a routine manner by means of a utility sub-routine.

A more sophisticated indicator would be to weight the fraction by the frequency of occurrence of the winds in that sector. The wind rose at the predicted site would not always be available so the reference site data would be the most practical set to use, but this may introduce an unwanted error due to the turning of the wind over the predicted site. A subroutine is necessary for this estimate as the handwork is too laborious. A further improvement would be to weight the terrain by the distance away from the site and whether or not it is situated up-stream or down-stream.

It is thought that more work on such refinements to the indicator should wait until it has been proven with a different set of reliable field data. However, the bulk of any future work would be best focussed on the improvement of the orographic model.

7 WAsP performance envelope

The operating envelope of WAsP cannot be defined quantitatively for all likely situations but it is dominated by the 4 main considerations listed below. Accurate predictions using the WAsP package may be obtained provided that both the reference and predicted sites are clearly:

a. Subject to the same weather regime

The maximum separation between sites would be best defined by the typical scale of the prevailing synoptic weather systems.

b. Prevailing weather conditions are close to being neutrally stable

Atmospheric effects are complex and no correction is available for use in non-neutrally stable conditions. However, it is expected that unstable conditions would increase any orographic error while stable conditions would decrease the error significantly. Coastal sites may be dominated by sea breezes, which do not reach other inland sites.

c. The surrounding terrain is not too steep

Prediction errors due to orography are likely to occur for sites with surrounding slopes significantly greater than 0.3. This slope is generally accepted to be the maximum to ensure predominantly attached flows. As the orographic prediction error depends on the difference in site ruggedness, accurate results may be possible between two rugged but similar sites. Large-scale terrain effects such as channelling must also be absent. Large differences in elevation should be treated with care.

d. High quality data

The measured wind speed data at the reference site, the preliminary data processing and sorting are all of high quality.

e. Proper use of the WAsP program

Great care must be taken to ensure reliable predictions when operating outside the limits. For sites with rugged terrain, an orographic performance indicator has been developed in this report, which should improve the interpretation of any such predictions.

8 Conclusions

The above discussion indicates that the WAsP model relies on a relatively simple climate model with a number of important assumptions. Prediction errors inevitably arise from the relative complexity of the real situation and are dominated by climatic and orographic effects.

a. WAsP prediction errors

- Prediction errors may be significant if the performance envelopes of WAsP for climate and terrain are exceeded.

b. Cross-correlation of wind speeds between the reference and predicted sites

- A high correlation is an essential but not exclusive pre-requisite for an accurate prediction.
- The value of the correlation does not indicate the sign or magnitude of the prediction error.

c. Orographic performance indicator

- The sign and approximate magnitude of the prediction error due to orography is proportional to the difference in ruggedness between the predicted and reference sites.
- A practical ruggedness index, RIX, is suggested, which is defined by the fractional extent of the terrain with slopes greater than a critical value.
- The approximate size and sign of the prediction error due to orography may be estimated using an orographic performance indicator.
- One suitable indicator is the difference in the ruggedness index, ΔRIX, between the predicted and reference sites.

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Appendices

Individual site maps and wind statistics for the selected sites in Northern Portugal used in the case study are given in the following six appendices, A to F, extracted from Petersen *et al*. (1996). For a detailed description of the various graphs and tables given for each station, the reader is further referred to Chapter 7 of the European Wind Atlas (Troen and Petersen, 1989).

A. Site 01 (Murtosa), pages 42-45

- General description
- Site map
- Wind statistics
- Site climatology

B. Site 06 (Pena), pages 46-49

- General description
- Site map
- Wind statistics
- Site climatology

C. Site 07 (Drave), pages 50-53

- General description
- Site map
- Wind statistics
- Site climatology

D. Site 08 (Arada), pages 54-57

- General description
- Site map
- Wind statistics
- Site climatology

E. Site 09 (Adaufe), pages 58-61

- General description
- Site map
- Wind statistics
- Site climatology

F. Site 10 (Castanheira), pages 62-65

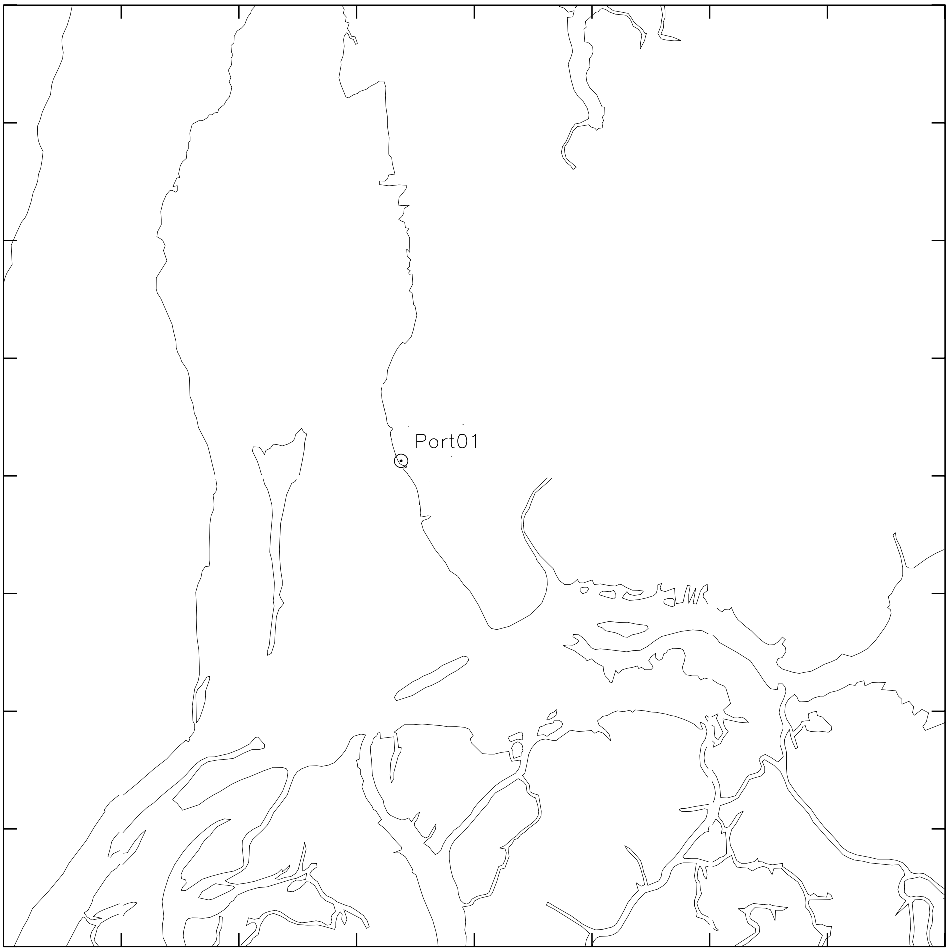
- General description
- Site map
- Wind statistics
- Site climatology

Station 01 (Murtosa) Portugal

40° 44′ 27″ N	08° 40′ 33″ W	UTM 29	E 527 375 m	N 4 510 125 m	1 m

The mast is situated close to the eastern coastline of the Ria de Aveiro, overlooking the bay to the W. The distance to the coastline is approx. 50 m and the bay is about 1 km or more wide. To the W the bay is bordered by a 2-km wide peninsula; the distance to the Atlantic coast is thus about 4 km. The land-use in the vicinity of the mast is agriculture and marsh, and about 2 km east of the mast is several small villages, the largest of which is Murtosa. There are no houses or other obstacles close to the mast.

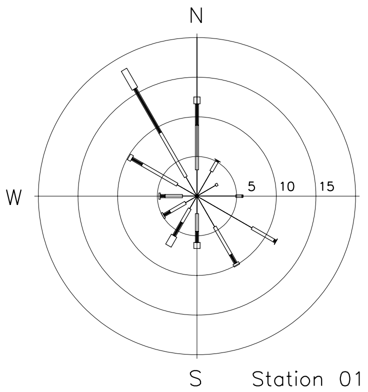
On the map below, the height contour interval is 50 m and 10 m, respectively, and tick marks are shown for every kilometer.

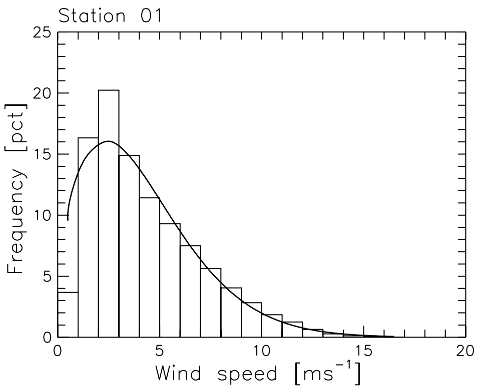


Sector	Input		Obstacles		Roughness		Orography		z_{0m}
0	0.0	0.0	0.0	0.0	−6.3	0.0	0.0	0.0	0.0093
30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0824
60	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0881
90	0.0	0.0	0.0	0.0	−7.6	0.0	0.0	0.0	0.0495
120	0.0	0.0	0.0	0.0	−11.9	0.0	0.0	0.0	0.0099
150	0.0	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0172
180	0.0	0.0	0.0	0.0	12.4	0.0	0.0	0.0	0.0088
210	0.0	0.0	0.0	0.0	14.6	0.0	0.0	0.0	0.0118
240	0.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0022
270	0.0	0.0	0.0	0.0	−1.9	0.0	0.0	0.0	0.0008
300	0.0	0.0	0.0	0.0	−0.2	0.0	0.0	0.0	0.0005
330	0.0	0.0	0.0	0.0	8.2	0.0	0.0	0.0	0.0037

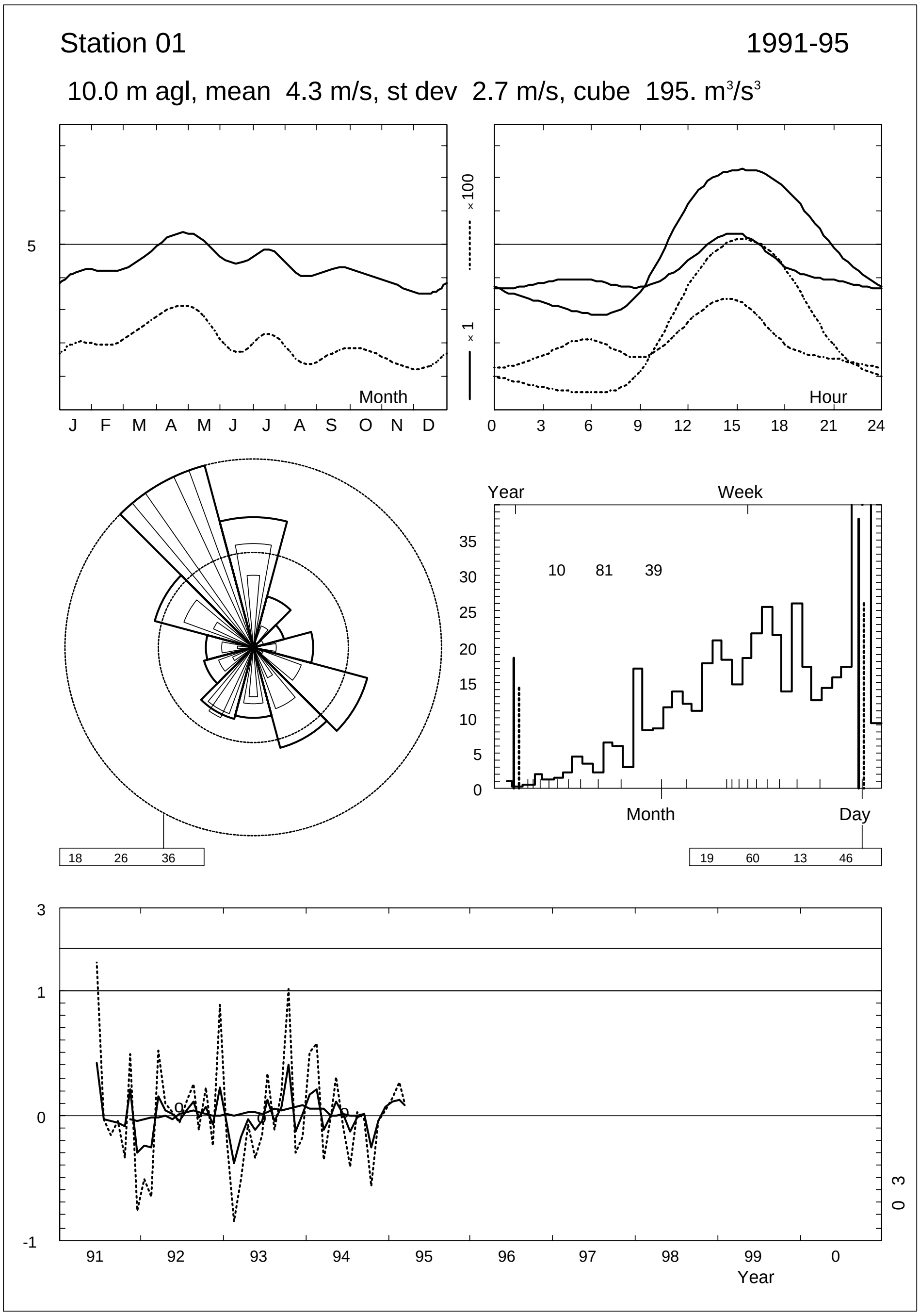
Height of anemometer: 10.0 m a.g.l. 199106251405 – 199503171535

Sect	Freq	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17	A	k
0	12.5	20	86	159	176	150	123	97	68	52	52	15	1	0	0	5.3	1.91
30	5.2	59	286	349	183	69	25	15	8	3	3	0	0	0	0	2.9	1.81
60	3.0	119	491	296	68	17	5	2	1	0	0	0	0	0	0	2.1	1.95
90	5.8	73	399	371	83	31	23	12	6	1	0	0	0	0	0	2.5	1.77
120	11.5	41	255	401	188	61	28	14	7	3	3	0	0	0	0	2.9	1.85
150	10.1	34	157	251	196	121	86	60	37	24	24	9	1	0	0	4.0	1.54
180	6.6	43	146	146	135	107	96	93	68	50	73	33	7	3	0	5.5	1.66
210	7.2	37	109	107	83	97	101	100	86	81	131	52	14	2	0	6.8	2.07
240	5.0	51	146	137	150	162	140	90	53	33	28	8	3	0	0	4.9	1.97
270	4.8	50	160	173	184	159	109	64	44	20	24	9	3	1	0	4.4	1.71
300	9.9	24	117	150	193	190	132	79	43	28	28	11	4	1	0	4.9	1.88
330	18.4	13	57	82	102	118	130	135	123	89	96	45	8	1	0	7.0	2.44
Total	100.0	37	163	202	149	114	93	75	56	40	47	19	4	1	0	4.7	1.54





	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	3.6	3.6	3.5	4.1	4.1	3.2	3.7	3.0	3.3	3.4	3.6	3.3	3.5
1	3.5	3.7	3.4	4.1	3.8	3.2	3.4	2.8	3.0	3.5	3.6	3.3	3.4
2	3.8	3.6	3.3	3.9	3.7	3.0	3.3	2.7	3.1	3.4	3.5	3.3	3.4
3	3.8	3.6	3.2	3.8	3.8	2.9	3.2	2.7	3.1	3.4	3.5	3.3	3.4
4	4.0	3.7	3.1	3.7	3.9	3.1	3.2	2.6	2.9	3.3	3.3	3.5	3.3
5	4.0	3.7	3.0	3.6	3.9	3.0	3.0	2.6	2.9	3.4	3.7	3.5	3.3
6	3.9	3.6	3.1	3.3	3.9	2.7	2.9	2.5	3.0	3.5	3.5	3.5	3.3
7	3.8	3.5	2.9	3.4	4.2	3.0	2.9	2.5	3.0	3.3	3.4	3.5	3.3
8	3.8	3.7	2.8	3.7	4.3	3.2	3.3	2.5	3.0	3.4	3.5	3.5	3.4
9	3.7	3.8	3.0	4.1	4.7	3.4	3.6	2.9	3.4	3.4	3.4	3.3	3.5
10	3.8	3.9	3.4	4.8	5.2	4.2	4.4	3.5	3.7	3.8	3.3	3.3	3.9
11	4.1	4.2	4.2	5.8	6.0	4.9	5.4	4.3	4.6	4.4	3.6	3.6	4.6
12	4.5	4.6	5.1	6.5	6.7	5.6	6.2	5.2	5.6	5.0	4.1	3.9	5.2
13	4.9	4.8	5.9	7.1	7.0	6.2	6.8	5.9	6.2	5.4	4.8	4.0	5.7
14	5.2	5.2	6.6	7.7	7.1	6.5	7.2	6.3	6.6	5.7	4.9	4.1	6.0
15	5.3	5.7	6.9	7.8	7.0	6.6	7.3	6.5	6.6	5.7	4.8	4.1	6.1
16	5.3	5.7	7.1	8.0	6.7	6.6	7.3	6.4	6.4	5.6	4.5	3.8	6.1
17	4.8	5.6	6.8	7.6	6.5	6.4	7.1	6.1	6.1	5.0	4.1	3.5	5.7
18	4.3	4.7	6.4	7.1	6.2	6.0	6.7	5.7	5.5	4.6	3.7	3.4	5.3
19	4.1	4.2	5.7	6.4	5.6	5.6	6.1	5.1	4.9	4.4	3.7	3.4	4.9
20	4.0	3.9	5.1	5.8	4.9	4.7	5.4	4.5	4.3	4.1	3.6	3.3	4.4
21	3.9	3.8	5.0	5.3	4.5	4.2	4.9	3.9	4.2	3.9	3.4	3.3	4.2
22	3.9	3.8	4.5	4.7	4.1	3.9	4.5	3.7	3.7	3.7	3.4	3.2	3.9
23	3.7	3.7	4.1	4.4	4.2	3.5	4.0	3.3	3.4	3.6	3.4	3.2	3.7
Mean	4.2	4.2	4.5	5.3	5.1	4.4	4.8	4.1	4.3	4.1	3.8	3.5	4.3



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1991	—	—	—	—	—	6.2	4.7	3.9	4.0	3.8	4.5	2.4	3.9
1992	3.2	3.1	5.2	5.5	5.1	4.2	5.0	4.5	4.2	4.4	3.5	4.3	4.3
1993	3.8	2.5	3.7	5.1	4.5	4.2	5.4	3.9	4.6	5.8	3.3	3.6	4.4
1994	4.9	5.1	4.0	5.3	5.6	4.5	4.2	4.0	4.3	3.0	3.6	3.7	4.3
1995	4.6	4.7	4.9	—	—	—	—	—	—	—	—	—	4.7
Mean	4.2	4.2	4.5	5.3	5.1	4.4	4.8	4.1	4.3	4.1	3.8	3.5	4.3

Roughness Class 0 ($z_0 = 0.0002$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	7.5	5.4	3.7	4.0	4.3	5.2	6.0	7.6	6.1	4.9	5.1	7.5	6.0
	2.40	1.87	2.08	2.05	2.15	1.76	1.85	2.31	2.15	1.80	1.89	2.68	1.93
25	8.2	5.9	4.1	4.4	4.8	5.7	6.6	8.3	6.6	5.4	5.6	8.3	6.6
	2.48	1.93	2.14	2.12	2.22	1.82	1.91	2.38	2.22	1.85	1.95	2.77	1.98
50	8.8	6.4	4.4	4.7	5.1	6.1	7.1	8.9	7.1	5.8	6.0	8.9	7.0
	2.55	1.98	2.20	2.17	2.28	1.87	1.96	2.44	2.28	1.90	2.00	2.84	2.02
100	9.6	6.9	4.8	5.1	5.5	6.6	7.7	9.6	7.7	6.3	6.5	9.6	7.6
	2.47	1.92	2.13	2.10	2.21	1.81	1.90	2.37	2.21	1.85	1.94	2.75	1.97
200	10.6	7.7	5.3	5.6	6.1	7.3	8.5	10.7	8.5	7.0	7.2	10.6	8.4
	2.33	1.82	2.02	1.99	2.09	1.71	1.80	2.24	2.09	1.75	1.84	2.60	1.88
Freq.	13.3	6.4	3.4	5.2	10.4	10.5	7.3	7.1	5.3	4.8	9.0	17.0	100.0

Roughness Class 1 ($z_0 = 0.0300$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	5.1	3.2	2.5	2.9	3.1	3.9	4.4	5.3	3.9	3.4	3.7	5.4	4.1
	1.89	1.74	1.90	1.74	1.72	1.54	1.63	1.97	1.90	1.51	1.58	2.32	1.67
25	6.1	3.9	3.0	3.5	3.7	4.7	5.3	6.4	4.7	4.1	4.5	6.5	5.0
	2.04	1.88	2.05	1.87	1.85	1.66	1.76	2.12	2.05	1.63	1.71	2.51	1.78
50	7.1	4.5	3.4	4.0	4.3	5.4	6.2	7.4	5.4	4.8	5.2	7.4	5.8
	2.30	2.11	2.31	2.10	2.08	1.87	1.98	2.39	2.31	1.83	1.92	2.82	1.96
100	8.4	5.3	4.1	4.8	5.1	6.4	7.4	8.8	6.5	5.7	6.2	8.8	6.9
	2.44	2.24	2.45	2.24	2.22	1.99	2.11	2.54	2.45	1.94	2.04	3.00	2.06
200	10.5	6.6	5.1	5.9	6.3	8.0	9.2	10.9	8.0	7.0	7.7	11.0	8.5
	2.33	2.14	2.35	2.14	2.12	1.90	2.01	2.43	2.35	1.86	1.95	2.87	1.99
Freq.	12.0	5.1	3.2	6.2	11.5	9.9	6.6	7.0	5.0	5.2	10.5	17.8	100.0

Roughness Class 2 ($z_0 = 0.1000$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	4.4	2.8	2.2	2.5	2.8	3.4	4.0	4.5	3.4	3.0	3.4	4.7	3.6
	1.85	1.80	1.84	1.82	1.78	1.55	1.68	1.92	1.88	1.52	1.60	2.30	1.68
25	5.4	3.5	2.7	3.2	3.5	4.2	4.9	5.6	4.2	3.7	4.2	5.8	4.5
	1.98	1.92	1.97	1.95	1.90	1.66	1.79	2.06	2.02	1.62	1.72	2.46	1.78
50	6.3	4.1	3.1	3.7	4.1	5.0	5.8	6.6	4.9	4.3	5.0	6.8	5.3
	2.19	2.13	2.18	2.16	2.11	1.83	1.98	2.28	2.23	1.79	1.90	2.73	1.94
100	7.6	4.8	3.7	4.4	4.9	5.9	6.9	7.8	5.9	5.2	5.9	8.1	6.3
	2.41	2.34	2.39	2.37	2.31	2.01	2.18	2.50	2.45	1.97	2.08	3.00	2.09
200	9.3	6.0	4.6	5.4	6.0	7.3	8.5	9.7	7.3	6.4	7.3	10.0	7.8
	2.30	2.24	2.29	2.27	2.21	1.92	2.09	2.39	2.35	1.89	1.99	2.87	2.02
Freq.	11.4	4.9	3.4	6.7	11.3	9.6	6.7	6.9	5.0	5.7	11.2	17.3	100.0

Roughness Class 3 ($z_0 = 0.4000$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	3.3	2.2	1.8	2.0	2.2	2.8	3.2	3.5	2.7	2.4	2.8	3.7	2.8
	1.80	1.73	1.89	1.76	1.62	1.60	1.73	1.87	1.87	1.58	1.65	2.25	1.67
25	4.4	2.8	2.4	2.7	2.9	3.6	4.2	4.6	3.5	3.2	3.8	4.8	3.8
	1.91	1.84	2.00	1.86	1.72	1.69	1.83	1.99	1.98	1.67	1.75	2.39	1.76
50	5.3	3.4	2.9	3.2	3.5	4.4	5.1	5.5	4.2	3.8	4.6	5.8	4.5
	2.07	1.99	2.17	2.02	1.87	1.84	1.99	2.16	2.15	1.82	1.90	2.60	1.88
100	6.4	4.1	3.5	3.9	4.3	5.3	6.2	6.7	5.1	4.6	5.5	7.0	5.5
	2.36	2.27	2.47	2.30	2.12	2.10	2.26	2.46	2.45	2.07	2.16	2.96	2.10
200	7.9	5.1	4.3	4.8	5.2	6.5	7.6	8.1	6.2	5.7	6.7	8.6	6.7
	2.27	2.19	2.38	2.22	2.05	2.02	2.18	2.37	2.36	1.99	2.08	2.85	2.04
Freq.	10.5	4.6	3.8	7.5	11.1	9.1	6.7	6.6	5.0	6.4	12.2	16.5	100.0

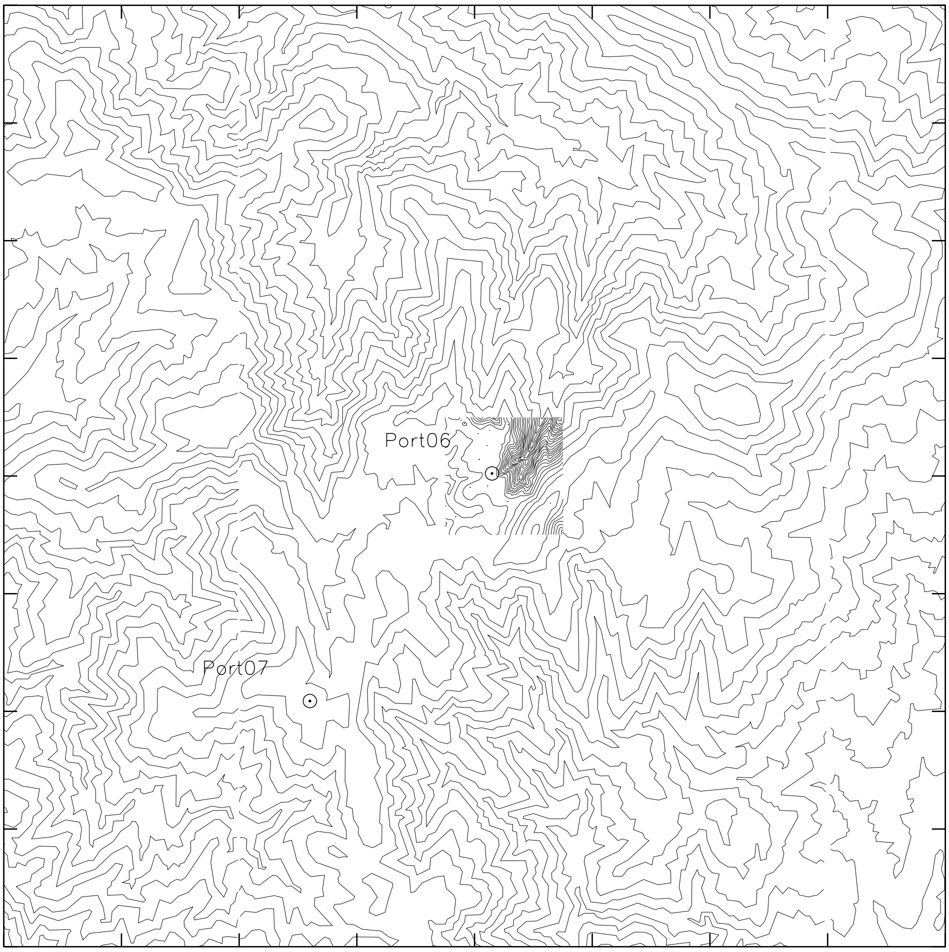
z	Class 0		Class 1		Class 2		Class 3	
m	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}
10	5.3	181	3.7	73	3.2	48	2.5	23
25	5.8	231	4.4	115	4.0	84	3.3	50
50	6.2	280	5.1	161	4.7	124	4.0	81
100	6.8	368	6.1	257	5.6	195	4.9	128
200	7.5	521	7.6	512	6.9	379	6.0	241

Station 06 (Pena) — Portugal

$40^\circ\ 52'\ 19''$ N	$08^\circ\ 05'\ 04''$ W	UTM 29	E 577 146 m	N 4 525 019 m	932 m

The mast is situated in the Serra de S. Macário mountains, about 1 km SSW of the village of Pena. The surface consists of grass and low, pillow-shaped bushes. Going E from the mast trees become more abundant and from a distance of 3–4 km the surface is covered by coniferous forest. There are no houses or other obstacles close to the mast.

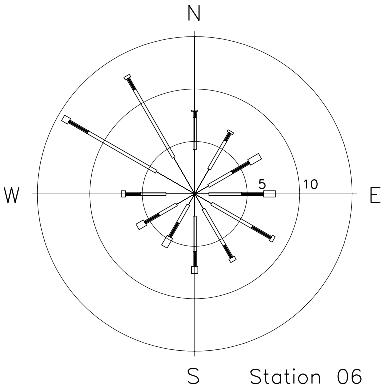
On the map below, the height contour interval is 50 m and 10 m, respectively, and tick marks are shown for every kilometer.

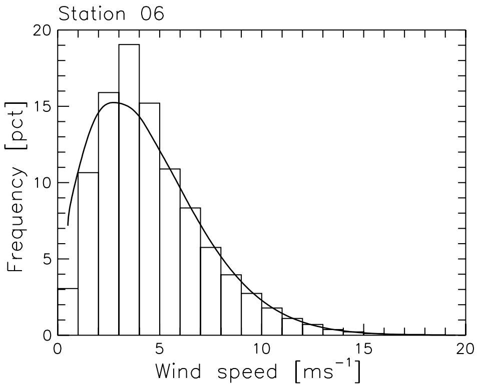


Sector	Input		Obstacles		Roughness		Orography		z_{0m}
0	0.0	0.0	0.0	0.0	0.0	0.0	51.9	4.8	0.0300
30	0.0	0.0	0.0	0.0	0.0	0.0	64.4	3.3	0.0300
60	0.0	0.0	0.0	0.0	0.0	0.0	67.6	−1.1	0.0300
90	0.0	0.0	0.0	0.0	0.0	0.0	58.8	−4.6	0.0300
120	0.0	0.0	0.0	0.0	0.0	0.0	45.8	−3.7	0.0300
150	0.0	0.0	0.0	0.0	0.0	0.0	42.1	1.4	0.0300
180	0.0	0.0	0.0	0.0	0.0	0.0	51.9	4.8	0.0300
210	0.0	0.0	0.0	0.0	0.0	0.0	64.4	3.3	0.0300
240	0.0	0.0	0.0	0.0	0.0	0.0	67.6	−1.1	0.0300
270	0.0	0.0	0.0	0.0	0.0	0.0	58.8	−4.6	0.0300
300	0.0	0.0	0.0	0.0	0.0	0.0	45.8	−3.7	0.0300
330	0.0	0.0	0.0	0.0	0.0	0.0	42.1	1.4	0.0300

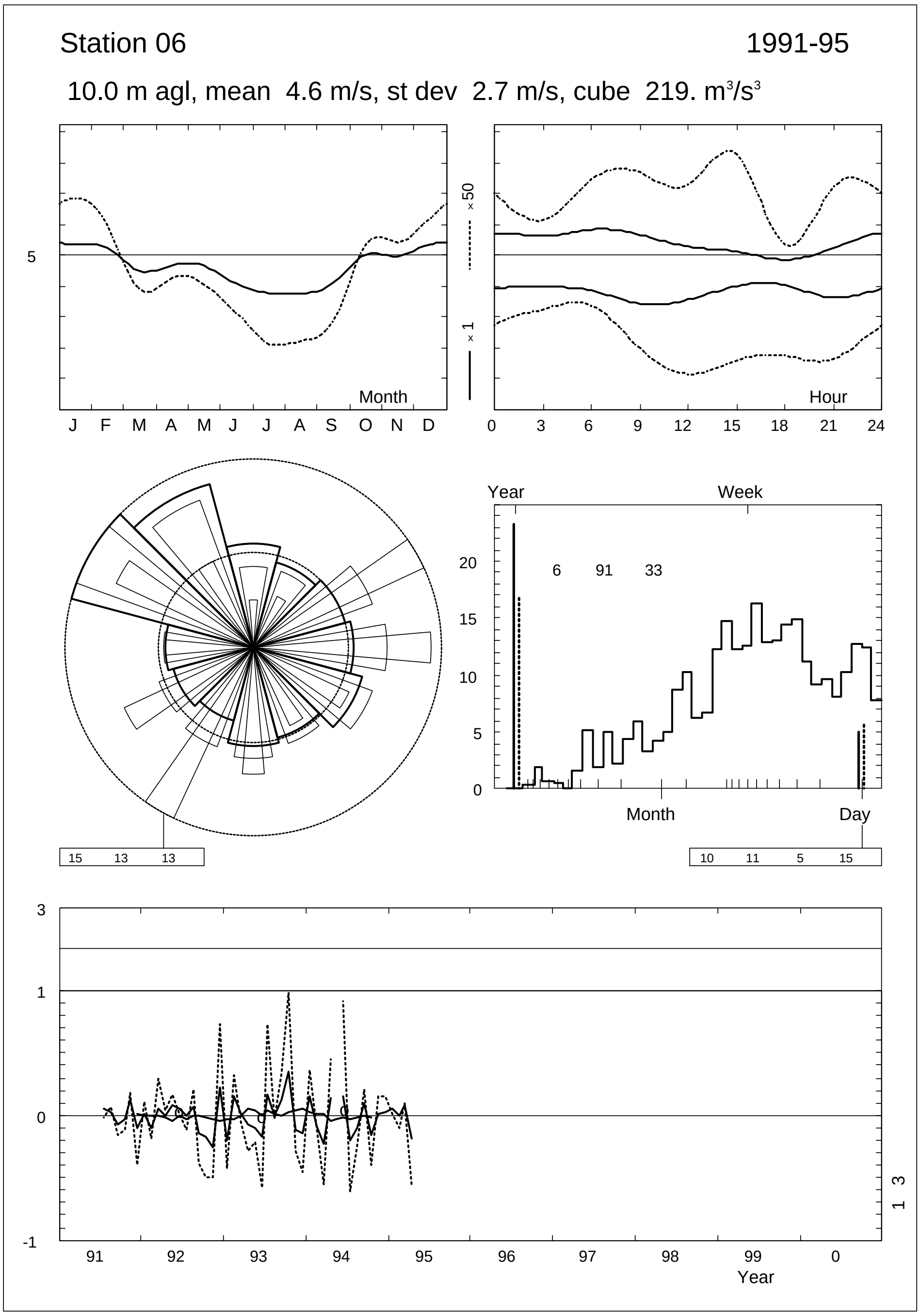
Height of anemometer: 10.0 m a.g.l. 199107111555 – 199504281325

Sect	Freq	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17	A	k
0	8.0	39	207	281	218	110	59	37	21	12	11	3	1	0	0	3.5	1.60
30	6.9	44	158	195	223	145	85	58	39	25	23	4	2	0	0	4.2	1.65
60	7.2	35	85	91	123	126	112	106	81	73	103	43	14	5	1	6.5	1.92
90	7.7	27	66	83	131	143	130	116	92	67	87	42	12	4	1	6.5	1.98
120	8.7	21	63	129	176	184	152	124	75	41	30	5	0	0	0	5.4	2.34
150	7.4	22	64	138	217	186	139	94	56	34	36	10	3	0	0	5.1	1.97
180	7.6	24	87	167	194	148	106	86	57	39	52	25	8	3	2	5.1	1.56
210	5.8	40	80	88	103	116	121	110	93	66	91	50	27	9	5	6.8	1.85
240	6.3	46	154	117	109	97	102	98	85	62	75	35	11	4	5	6.0	1.74
270	7.0	45	173	173	134	117	94	91	68	47	39	13	4	1	0	4.8	1.66
300	14.5	23	86	183	253	171	97	66	45	31	33	10	2	0	0	4.6	1.69
330	13.0	22	94	192	260	203	113	55	25	15	15	5	1	0	0	4.4	2.00
Total	100.0	31	107	159	190	152	109	83	58	40	45	18	6	2	1	5.0	1.65





	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	5.7	5.4	4.4	4.8	4.5	3.8	3.9	3.4	3.9	5.1	4.9	5.4	4.6
1	5.7	5.5	4.6	4.8	4.7	4.3	4.0	3.6	3.9	5.2	4.9	5.4	4.7
2	5.7	5.5	4.8	4.7	4.7	4.2	4.0	3.7	4.0	5.3	5.2	5.4	4.8
3	5.6	5.5	4.9	4.7	4.8	4.4	4.0	3.7	4.1	5.6	5.1	5.5	4.8
4	5.9	5.4	4.7	4.8	4.5	4.4	3.7	3.8	4.3	5.5	5.2	5.5	4.8
5	5.8	5.5	4.6	4.9	4.7	4.4	3.9	3.8	4.4	5.3	5.1	5.5	4.8
6	5.8	5.6	4.7	4.9	4.4	4.7	3.8	3.8	4.3	5.3	5.1	5.4	4.8
7	5.6	5.9	4.9	4.9	4.5	4.6	3.8	3.9	4.3	5.4	5.2	5.6	4.9
8	5.4	5.5	4.5	4.8	4.8	4.2	3.5	3.9	4.3	5.0	4.9	5.6	4.7
9	5.7	5.4	4.7	4.5	4.8	4.2	3.4	3.8	4.1	5.0	4.9	5.5	4.7
10	5.4	5.5	4.4	4.4	5.2	3.9	3.3	3.5	3.9	5.0	4.9	5.5	4.5
11	5.3	5.2	4.5	4.4	5.2	3.8	3.4	3.6	3.9	5.0	5.0	5.4	4.5
12	5.3	5.3	4.4	4.6	4.9	3.8	3.6	3.8	4.0	5.0	4.8	5.3	4.6
13	5.2	4.8	4.4	4.8	5.2	3.9	3.8	4.1	4.1	4.7	4.7	5.1	4.5
14	5.3	4.9	4.4	4.9	5.1	3.9	3.9	4.1	4.1	4.9	4.8	5.0	4.6
15	5.1	4.7	4.1	4.8	4.9	4.3	4.0	4.4	4.2	4.7	4.7	5.1	4.6
16	4.8	4.6	4.2	4.8	4.9	4.0	4.0	4.2	4.4	4.5	4.6	4.7	4.5
17	4.6	4.4	4.5	4.7	4.7	4.1	4.2	4.1	4.4	4.8	4.8	4.8	4.5
18	4.9	4.6	4.3	4.8	4.3	4.0	4.0	4.1	4.2	4.8	4.7	5.2	4.5
19	4.9	4.9	4.2	4.6	4.1	3.8	3.8	3.7	4.1	4.8	5.0	5.2	4.5
20	5.1	5.3	4.4	4.5	4.1	3.6	3.6	3.4	3.8	4.8	5.0	5.6	4.5
21	5.2	5.2	4.5	4.5	4.1	3.8	3.6	3.3	3.9	5.0	5.1	5.5	4.5
22	5.3	5.3	4.4	4.3	4.0	3.7	3.6	3.4	3.9	5.0	5.0	5.5	4.5
23	5.4	5.2	4.5	4.4	4.5	3.8	3.6	3.4	3.9	5.0	5.2	5.6	4.5
Mean	5.4	5.2	4.5	4.7	4.6	4.1	3.8	3.8	4.1	5.0	5.0	5.4	4.6



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1991	—	—	—	—	—	—	4.0	3.8	3.8	4.9	5.6	4.8	4.5
1992	5.4	4.7	4.7	4.7	5.0	4.3	3.8	4.0	3.5	4.2	3.7	6.6	4.6
1993	4.3	6.0	4.5	4.3	4.2	3.4	4.4	3.8	4.6	6.8	4.4	4.6	4.6
1994	6.2	4.8	3.5	5.3	4.4	4.7	3.0	3.4	4.5	4.2	5.0	5.5	4.5
1995	5.7	5.2	4.9	3.8	—	—	—	—	—	—	—	—	5.1
Mean	5.4	5.2	4.5	4.7	4.6	4.1	3.8	3.8	4.1	5.0	5.0	5.4	4.6

Roughness Class 0 ($z_0 = 0.0002$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	3.8	3.6	5.1	5.8	5.5	5.3	5.1	5.6	5.4	4.6	4.6	4.4	4.8
	2.08	1.90	2.06	2.33	2.57	2.38	1.99	2.07	2.10	1.98	2.02	2.25	2.05
25	4.2	3.9	5.5	6.3	6.0	5.8	5.6	6.2	5.9	5.1	5.0	4.9	5.3
	2.15	1.96	2.13	2.41	2.65	2.45	2.05	2.13	2.16	2.04	2.08	2.32	2.11
50	4.5	4.2	5.9	6.8	6.4	6.2	6.1	6.6	6.3	5.4	5.4	5.2	5.7
	2.20	2.01	2.19	2.47	2.72	2.52	2.11	2.19	2.22	2.09	2.14	2.38	2.16
100	4.9	4.6	6.4	7.4	7.0	6.7	6.6	7.2	6.8	5.9	5.8	5.7	6.2
	2.13	1.94	2.12	2.40	2.63	2.44	2.04	2.12	2.15	2.03	2.07	2.31	2.10
200	5.4	5.1	7.1	8.2	7.7	7.4	7.2	7.9	7.6	6.5	6.4	6.3	6.8
	2.02	1.84	2.00	2.27	2.49	2.31	1.93	2.01	2.04	1.92	1.96	2.19	1.99
Freq.	9.8	6.8	6.3	7.0	8.8	8.7	7.9	5.9	5.4	6.3	12.7	14.5	100.0

Roughness Class 1 ($z_0 = 0.0300$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	2.4	2.7	3.9	4.1	3.8	3.7	3.5	4.1	3.6	3.1	3.2	3.1	3.4
	1.63	1.69	1.91	1.98	2.23	1.95	1.60	1.83	1.72	1.64	1.68	1.98	1.74
25	2.9	3.2	4.7	4.9	4.5	4.4	4.3	5.0	4.3	3.8	3.8	3.7	4.1
	1.76	1.83	2.07	2.14	2.41	2.11	1.73	1.98	1.85	1.77	1.81	2.13	1.87
50	3.4	3.7	5.4	5.7	5.2	5.1	5.0	5.7	5.0	4.4	4.4	4.3	4.7
	1.98	2.05	2.32	2.40	2.71	2.37	1.94	2.22	2.08	1.99	2.03	2.40	2.09
100	4.0	4.4	6.4	6.7	6.2	6.0	5.9	6.8	5.9	5.2	5.2	5.1	5.6
	2.10	2.19	2.47	2.56	2.88	2.52	2.06	2.37	2.21	2.12	2.16	2.55	2.21
200	5.0	5.5	8.0	8.4	7.7	7.5	7.3	8.5	7.4	6.4	6.5	6.3	6.9
	2.01	2.09	2.36	2.44	2.76	2.41	1.97	2.26	2.12	2.03	2.06	2.44	2.12
Freq.	8.2	6.2	6.2	7.3	9.4	8.5	7.7	5.3	5.4	6.6	14.8	14.3	100.0

Roughness Class 2 ($z_0 = 0.1000$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	2.1	2.4	3.4	3.5	3.3	3.2	3.1	3.6	3.1	2.8	2.8	2.7	3.0
	1.58	1.63	1.91	1.99	2.16	1.88	1.61	1.82	1.69	1.70	1.79	2.03	1.76
25	2.6	3.0	4.2	4.4	4.1	3.9	3.9	4.4	3.8	3.4	3.5	3.4	3.7
	1.69	1.74	2.05	2.13	2.31	2.01	1.72	1.95	1.81	1.81	1.91	2.17	1.87
50	3.1	3.5	4.9	5.1	4.7	4.6	4.6	5.2	4.5	4.0	4.1	3.9	4.3
	1.87	1.92	2.27	2.36	2.56	2.22	1.90	2.15	2.00	2.01	2.12	2.40	2.06
100	3.7	4.2	5.9	6.1	5.6	5.5	5.4	6.2	5.3	4.8	4.9	4.7	5.1
	2.05	2.12	2.49	2.59	2.81	2.45	2.09	2.37	2.20	2.20	2.33	2.64	2.25
200	4.5	5.2	7.3	7.5	7.0	6.8	6.7	7.6	6.6	5.9	6.0	5.8	6.3
	1.97	2.03	2.38	2.48	2.69	2.34	2.00	2.26	2.10	2.11	2.22	2.53	2.16
Freq.	7.9	6.2	6.3	7.5	9.3	8.5	7.4	5.3	5.6	7.3	14.8	13.9	100.0

Roughness Class 3 ($z_0 = 0.4000$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	1.8	2.0	2.7	2.8	2.6	2.5	2.5	2.8	2.4	2.2	2.2	2.1	2.3
	1.73	1.62	1.96	2.04	2.21	1.90	1.67	1.81	1.67	1.66	1.69	1.87	1.76
25	2.3	2.6	3.6	3.7	3.4	3.3	3.3	3.6	3.1	2.8	2.8	2.7	3.1
	1.83	1.71	2.08	2.16	2.34	2.02	1.77	1.92	1.77	1.76	1.79	1.98	1.85
50	2.8	3.2	4.3	4.4	4.2	4.0	4.1	4.4	3.8	3.5	3.5	3.3	3.7
	1.99	1.86	2.26	2.35	2.55	2.19	1.92	2.09	1.92	1.91	1.95	2.15	2.01
100	3.4	3.9	5.2	5.3	5.0	4.8	4.9	5.3	4.6	4.2	4.2	4.0	4.5
	2.26	2.12	2.57	2.68	2.90	2.49	2.19	2.38	2.19	2.17	2.22	2.45	2.26
200	4.2	4.7	6.4	6.5	6.1	5.9	6.0	6.5	5.6	5.1	5.1	4.8	5.5
	2.18	2.04	2.48	2.58	2.79	2.40	2.11	2.29	2.11	2.10	2.14	2.36	2.19
Freq.	7.7	6.2	6.5	7.8	9.2	8.4	7.1	5.3	5.7	8.5	14.8	13.1	100.0

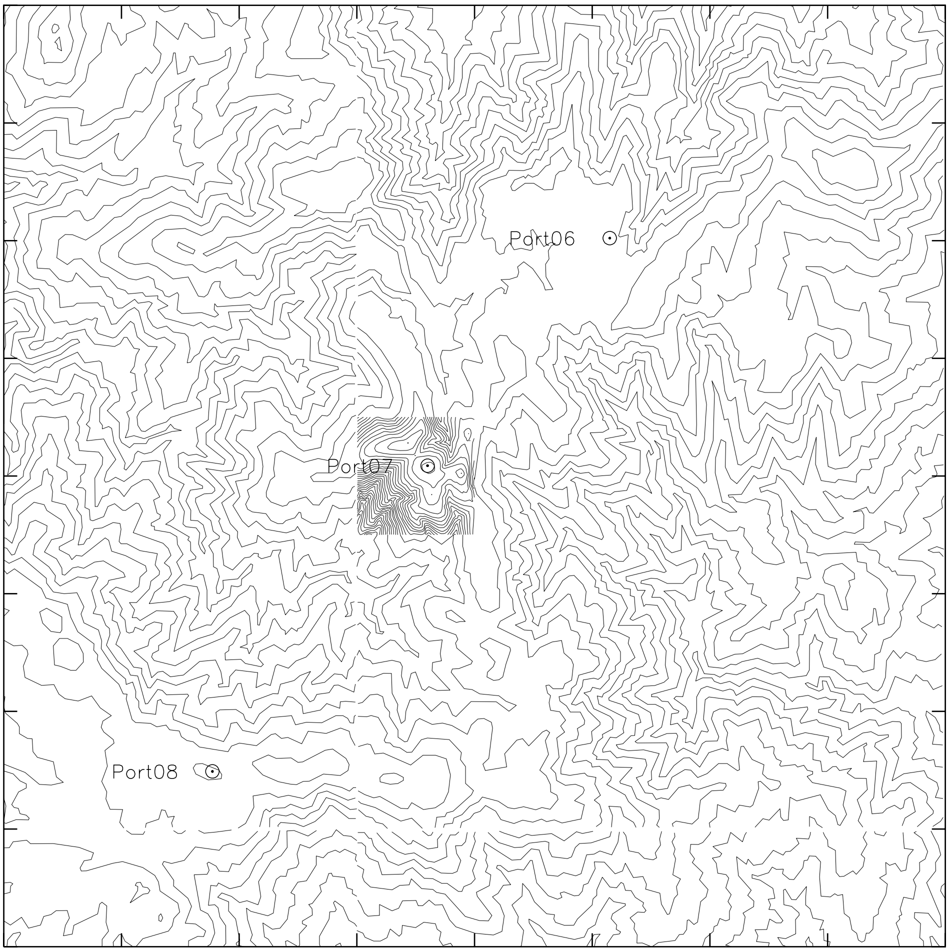
z	Class 0		Class 1		Class 2		Class 3	
m	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}
10	4.3	89	3.0	36	2.6	24	2.1	12
25	4.7	113	3.6	58	3.2	42	2.7	25
50	5.0	138	4.2	80	3.8	62	3.3	41
100	5.5	180	4.9	128	4.5	98	4.0	66
200	6.0	256	6.1	256	5.6	191	4.9	123

Station 07 (Drave) Portugal

40° 51′ 17″ N 08° 06′ 11″ W	UTM 29 E 575 598 m N 4 523 085 m	982 m

The mast is situated in the southern part of the Serra de S. Macário mountains, about 1.5 km SE of the village of Drave. The surface consists of low scrub. Going E and SE from the mast trees become more abundant and from a distance of 4–5 km the surface is covered by coniferous forest. There are no houses or other obstacles close to the mast.

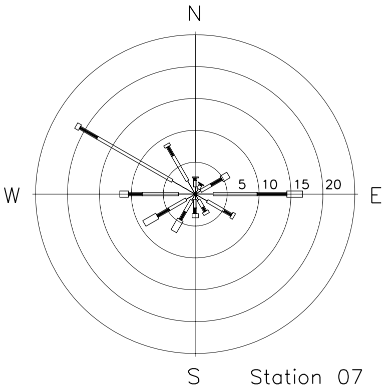
On the map below, the height contour interval is 50 m and 10 m, respectively, and tick marks are shown for every kilometer.

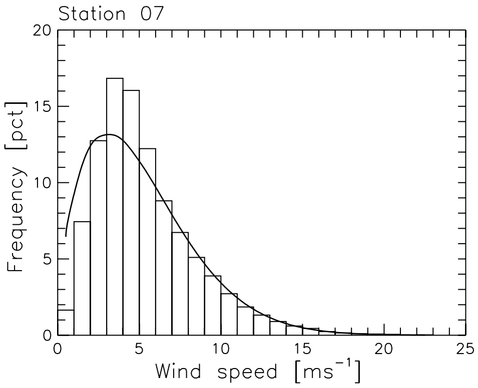


Sector	Input		Obstacles		Roughness		Orography		z_{0m}
0	0.0	0.0	0.0	0.0	0.0	0.0	61.5	1.6	0.0300
30	0.0	0.0	0.0	0.0	0.0	0.0	76.5	6.4	0.0300
60	0.0	0.0	0.0	0.0	0.0	0.0	96.0	4.4	0.0300
90	0.0	0.0	0.0	0.0	0.0	0.0	101.4	−1.3	0.0300
120	0.0	0.0	0.0	0.0	0.0	0.0	88.4	−6.0	0.0300
150	0.0	0.0	0.0	0.0	0.0	0.0	68.1	−5.1	0.0300
180	0.0	0.0	0.0	0.0	0.0	0.0	61.5	1.6	0.0300
210	0.0	0.0	0.0	0.0	0.0	0.0	76.5	6.4	0.0300
240	0.0	0.0	0.0	0.0	0.0	0.0	96.0	4.4	0.0300
270	0.0	0.0	0.0	0.0	0.0	0.0	101.4	−1.3	0.0300
300	0.0	0.0	0.0	0.0	0.0	0.0	88.4	−6.0	0.0300
330	0.0	0.0	0.0	0.0	0.0	0.0	68.1	−5.1	0.0300

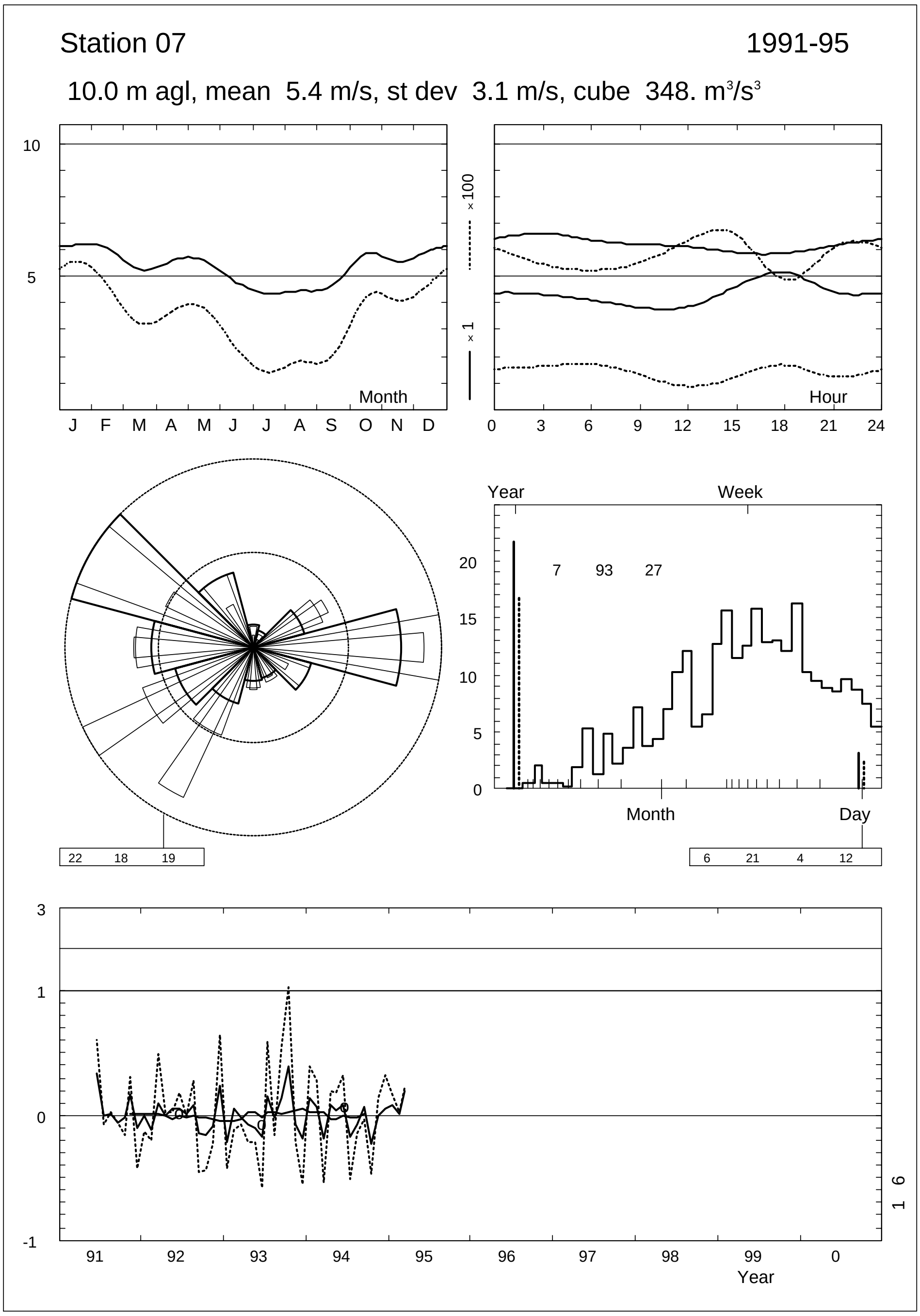
Height of anemometer: 10.0 m a.g.l. 199106301535 – 199502161005

Sect	Freq	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17	A	k
0	2.7	49	171	200	161	123	97	70	47	29	37	12	4	1	0	4.4	1.52
30	1.9	71	230	195	155	106	74	51	35	26	32	17	7	2	1	3.9	1.28
60	6.0	20	70	78	86	107	117	115	114	88	125	53	18	6	2	7.3	2.23
90	16.8	9	51	107	135	140	134	107	92	77	99	38	8	2	0	6.5	2.07
120	7.0	21	114	174	168	148	122	85	60	43	46	15	4	0	0	5.1	1.79
150	3.6	32	112	141	137	123	115	94	66	48	74	36	21	2	0	5.8	1.68
180	3.7	30	86	109	128	129	110	95	77	63	103	47	20	4	0	6.4	1.82
210	6.7	17	64	82	101	113	97	81	71	65	109	82	58	35	25	8.0	1.68
240	9.2	17	69	93	125	116	92	88	77	66	101	65	45	24	21	7.4	1.63
270	11.8	16	73	132	190	173	116	76	61	47	56	29	16	8	6	5.4	1.46
300	21.5	7	49	137	242	237	149	80	43	23	21	7	2	1	0	5.0	2.10
330	9.0	14	84	168	208	174	123	85	59	38	31	11	3	2	0	5.0	1.83
Total	100.0	16	74	127	168	160	122	88	67	51	66	32	15	7	4	5.7	1.59





	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	6.4	6.4	5.2	5.5	5.3	4.6	4.4	4.1	4.4	5.8	5.6	5.9	5.3
1	6.4	6.3	5.4	5.6	5.5	4.9	4.4	4.4	4.4	6.0	5.6	6.1	5.4
2	6.5	6.2	5.5	5.5	5.5	4.9	4.4	4.3	4.4	6.1	5.7	6.0	5.4
3	6.6	5.9	5.6	5.5	5.7	4.7	4.3	4.3	4.7	6.2	5.8	6.2	5.5
4	6.5	5.9	5.5	5.6	5.5	4.8	4.3	4.5	4.9	6.1	6.0	6.3	5.5
5	6.5	6.0	5.3	5.7	5.3	5.1	4.2	4.4	4.9	6.0	5.8	6.1	5.4
6	6.4	6.1	5.2	5.8	5.4	5.0	4.1	4.5	4.8	6.1	5.7	6.3	5.4
7	6.4	6.2	5.3	5.5	5.3	4.9	4.1	4.5	4.8	6.0	5.5	6.1	5.4
8	6.2	5.9	5.2	5.6	5.5	5.1	4.0	4.4	4.7	5.6	5.6	6.3	5.3
9	6.2	6.1	5.2	5.5	5.5	4.9	3.8	4.3	4.4	5.7	5.6	6.1	5.3
10	6.1	6.3	5.1	5.3	5.8	4.6	3.7	4.0	4.3	5.8	5.2	6.0	5.2
11	6.2	6.1	5.1	5.3	5.8	4.5	3.8	4.2	4.5	6.0	5.3	5.9	5.2
12	6.1	6.5	5.0	5.6	6.0	4.5	3.9	4.1	4.5	5.9	5.4	5.9	5.3
13	6.0	6.1	5.0	5.7	6.3	4.5	4.2	4.4	4.7	5.6	5.3	5.9	5.3
14	5.9	6.0	5.1	5.8	6.1	4.8	4.4	4.5	4.9	5.8	5.5	5.8	5.4
15	5.9	5.9	5.1	5.9	6.0	4.8	4.6	4.9	4.9	5.9	5.4	5.8	5.4
16	5.9	5.8	5.1	5.8	5.9	4.7	4.8	5.1	4.9	5.5	5.2	5.6	5.4
17	5.5	5.8	5.3	5.9	5.7	4.9	5.0	5.1	5.0	5.8	5.4	5.7	5.4
18	5.9	5.8	5.4	5.8	5.8	5.0	5.2	5.1	5.1	5.8	5.4	5.8	5.5
19	5.9	5.8	5.4	5.9	5.6	5.0	5.0	5.1	5.1	5.7	5.5	5.9	5.5
20	5.9	6.1	5.5	5.6	5.4	4.8	4.8	4.6	4.8	5.8	5.7	6.0	5.4
21	6.2	6.1	5.2	5.4	5.0	4.7	4.4	4.3	4.6	5.8	5.6	6.0	5.3
22	6.3	6.2	5.4	5.4	5.1	4.7	4.2	4.2	4.5	5.9	5.6	6.1	5.3
23	6.4	6.2	5.4	5.3	5.3	4.6	4.4	4.1	4.3	5.9	5.7	6.1	5.3
Mean	6.2	6.1	5.3	5.6	5.6	4.8	4.4	4.5	4.7	5.9	5.5	6.0	5.4



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1991	—	—	—	—	—	6.4	4.4	4.5	4.4	5.8	6.5	5.4	5.2
1992	6.1	5.4	5.8	5.6	5.9	5.1	4.4	4.8	4.0	5.0	5.0	7.4	5.4
1993	4.9	6.4	5.2	5.2	5.1	4.0	5.0	4.4	5.3	8.2	5.1	4.9	5.3
1994	7.0	6.4	4.3	6.1	5.9	5.2	3.6	4.1	5.0	4.6	5.6	6.3	5.3
1995	6.7	6.1	6.3	—	—	—	—	—	—	—	—	—	6.4
Mean	6.2	6.1	5.3	5.6	5.6	4.8	4.4	4.5	4.7	5.9	5.5	6.0	5.4

Roughness Class 0 ($z_0 = 0.0002$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	4.1	4.2	5.1	4.7	4.3	4.5	5.6	6.4	5.6	4.2	3.9	4.1	4.6
	2.08	1.82	2.49	2.49	2.28	1.99	1.98	1.99	1.90	1.74	2.24	2.27	1.92
25	4.5	4.6	5.6	5.1	4.7	4.9	6.2	7.0	6.1	4.7	4.2	4.5	5.0
	2.15	1.87	2.58	2.56	2.36	2.06	2.05	2.05	1.96	1.79	2.31	2.34	1.98
50	4.9	5.0	6.0	5.5	5.1	5.3	6.6	7.5	6.6	5.0	4.5	4.8	5.4
	2.20	1.92	2.64	2.63	2.42	2.11	2.10	2.11	2.01	1.83	2.37	2.40	2.03
100	5.3	5.4	6.6	6.0	5.5	5.8	7.2	8.1	7.2	5.4	4.9	5.2	5.9
	2.13	1.86	2.56	2.55	2.34	2.05	2.03	2.04	1.95	1.78	2.30	2.33	1.97
200	5.8	5.9	7.3	6.6	6.1	6.4	7.9	9.0	7.9	6.0	5.4	5.8	6.5
	2.02	1.76	2.42	2.41	2.22	1.94	1.92	1.93	1.85	1.69	2.18	2.20	1.87
Freq.	5.9	3.0	5.0	11.8	9.3	5.5	4.8	6.8	8.0	9.3	16.5	14.1	100.0

Roughness Class 1 ($z_0 = 0.0300$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	2.8	3.0	3.7	3.2	2.9	3.3	4.1	4.4	3.7	2.8	2.7	3.0	3.2
	1.60	1.54	2.17	2.06	1.85	1.67	1.72	1.64	1.59	1.52	2.06	1.91	1.66
25	3.4	3.6	4.4	3.9	3.5	4.0	4.9	5.3	4.5	3.4	3.3	3.6	3.9
	1.73	1.66	2.35	2.22	1.99	1.79	1.86	1.77	1.72	1.65	2.22	2.06	1.78
50	4.0	4.2	5.1	4.4	4.1	4.6	5.7	6.2	5.2	3.9	3.8	4.2	4.5
	1.94	1.87	2.64	2.50	2.24	2.02	2.09	1.99	1.93	1.85	2.50	2.31	1.97
100	4.7	5.1	6.0	5.3	4.8	5.5	6.8	7.3	6.2	4.7	4.5	4.9	5.3
	2.06	1.99	2.81	2.67	2.38	2.15	2.22	2.12	2.05	1.97	2.67	2.46	2.09
200	5.9	6.3	7.5	6.6	6.0	6.8	8.5	9.1	7.7	5.8	5.6	6.1	6.6
	1.97	1.90	2.69	2.55	2.28	2.05	2.12	2.03	1.96	1.88	2.55	2.35	2.01
Freq.	3.5	2.8	5.9	13.8	7.7	4.7	4.8	7.5	8.2	9.8	18.9	12.4	100.0

Roughness Class 2 ($z_0 = 0.1000$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	2.5	2.8	3.1	2.8	2.6	3.0	3.6	3.8	3.1	2.5	2.4	2.7	2.8
	1.58	1.65	2.14	2.10	1.85	1.67	1.71	1.65	1.56	1.58	2.03	1.97	1.67
25	3.1	3.4	3.8	3.5	3.2	3.7	4.5	4.7	3.9	3.0	3.0	3.3	3.5
	1.69	1.76	2.29	2.25	1.98	1.79	1.83	1.76	1.67	1.69	2.17	2.10	1.78
50	3.6	4.0	4.5	4.1	3.8	4.3	5.3	5.6	4.6	3.6	3.5	3.8	4.1
	1.87	1.95	2.53	2.49	2.19	1.98	2.02	1.95	1.84	1.87	2.40	2.33	1.96
100	4.3	4.8	5.3	4.9	4.5	5.2	6.3	6.7	5.5	4.3	4.1	4.6	4.9
	2.05	2.14	2.79	2.74	2.40	2.18	2.22	2.14	2.02	2.05	2.64	2.56	2.13
200	5.3	5.9	6.6	6.0	5.5	6.4	7.8	8.2	6.7	5.3	5.1	5.7	6.0
	1.97	2.05	2.67	2.62	2.30	2.08	2.13	2.05	1.94	1.97	2.53	2.45	2.04
Freq.	3.4	3.1	6.7	13.2	7.4	4.7	5.1	7.6	8.4	10.7	18.2	11.6	100.0

Roughness Class 3 ($z_0 = 0.4000$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	2.0	2.3	2.4	2.2	2.1	2.4	2.9	2.9	2.4	1.9	1.9	2.1	2.2
	1.59	1.74	2.07	1.99	1.79	1.68	1.72	1.64	1.52	1.64	1.96	1.84	1.65
25	2.6	3.0	3.1	2.9	2.7	3.2	3.8	3.9	3.1	2.5	2.5	2.7	2.9
	1.68	1.84	2.20	2.11	1.90	1.78	1.82	1.74	1.61	1.74	2.08	1.95	1.75
50	3.2	3.6	3.8	3.5	3.3	3.9	4.6	4.7	3.8	3.1	3.0	3.3	3.5
	1.83	2.00	2.39	2.30	2.06	1.94	1.98	1.89	1.74	1.88	2.26	2.12	1.88
100	3.9	4.3	4.5	4.2	4.0	4.7	5.6	5.7	4.6	3.7	3.7	4.0	4.3
	2.08	2.28	2.72	2.62	2.35	2.20	2.25	2.15	1.98	2.15	2.57	2.41	2.12
200	4.7	5.3	5.6	5.2	4.9	5.7	6.8	7.0	5.6	4.5	4.5	4.8	5.2
	2.00	2.20	2.62	2.52	2.27	2.12	2.17	2.08	1.91	2.07	2.48	2.33	2.05
Freq.	3.3	3.5	7.8	12.4	6.9	4.7	5.4	7.7	8.7	12.0	17.2	10.4	100.0

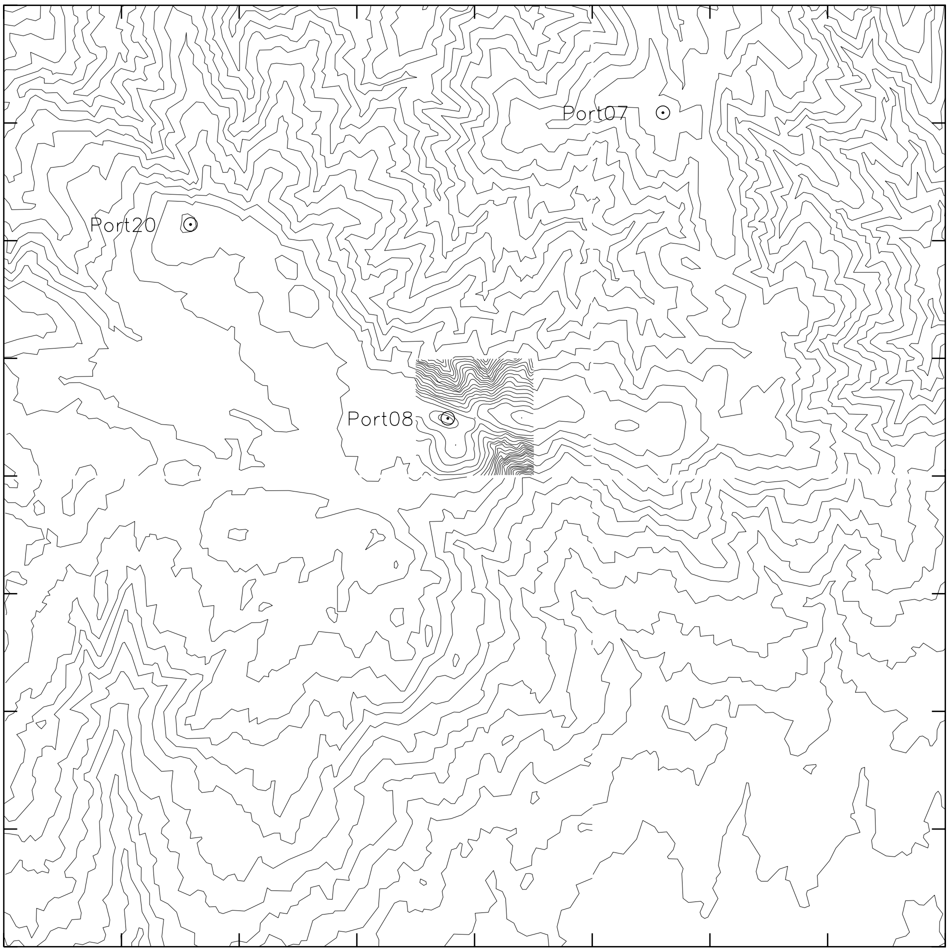
z	Class 0		Class 1		Class 2		Class 3	
m	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}
10	4.1	82	2.9	34	2.5	22	2.0	11
25	4.5	104	3.4	53	3.1	39	2.6	23
50	4.8	126	4.0	74	3.6	57	3.1	38
100	5.2	165	4.7	117	4.3	90	3.8	60
200	5.7	236	5.9	235	5.4	176	4.6	113

Station 08 (Arada) — Portugal

40° 49′ 53″ N	08° 07′ 30″ W	UTM 29	E 573 770 m	N 4 520 487 m	1057 m

The mast is situated on a mountain ridge, Serra de Arada, about 750 m N of the village of Arada. The surface consists of a homogeneous cover of low scrub. To the S and SSE, from a distance of about 3 km, the land-use changes to forest and there are numerous small villages. There are no houses or other obstacles close to the mast.

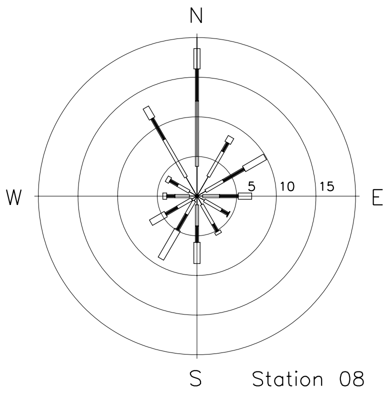
On the map below, the height contour interval is 50 m and 10 m, respectively, and tick marks are shown for every kilometer.

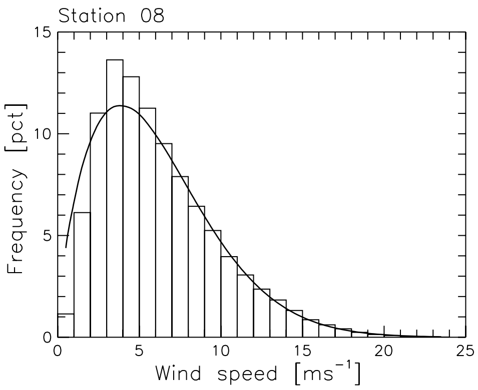


Sector	Input		Obstacles		Roughness		Orography		$z_{0\mathrm{m}}$
0	0.0	0.0	0.0	0.0	0.0	0.0	151.0	−0.1	0.0300
30	0.0	0.0	0.0	0.0	0.0	0.0	125.5	−14.3	0.0300
60	0.0	0.0	0.0	0.0	0.0	0.0	63.9	−19.8	0.0300
90	0.0	0.0	0.0	0.0	0.0	0.0	22.5	0.2	0.0300
120	0.0	0.0	0.0	0.0	0.0	0.0	64.8	19.8	0.0300
150	0.0	0.0	0.0	0.0	0.0	0.0	126.1	14.2	0.0300
180	0.0	0.0	0.0	0.0	0.0	0.0	151.0	−0.1	0.0300
210	0.0	0.0	0.0	0.0	0.0	0.0	125.5	−14.3	0.0300
240	0.0	0.0	0.0	0.0	0.0	0.0	63.9	−19.8	0.0300
270	0.0	0.0	0.0	0.0	0.0	0.0	22.5	0.2	0.0300
300	0.0	0.0	0.0	0.0	0.0	0.0	64.8	19.8	0.0300
330	0.0	0.0	0.0	0.0	0.0	0.0	126.1	14.2	0.0300

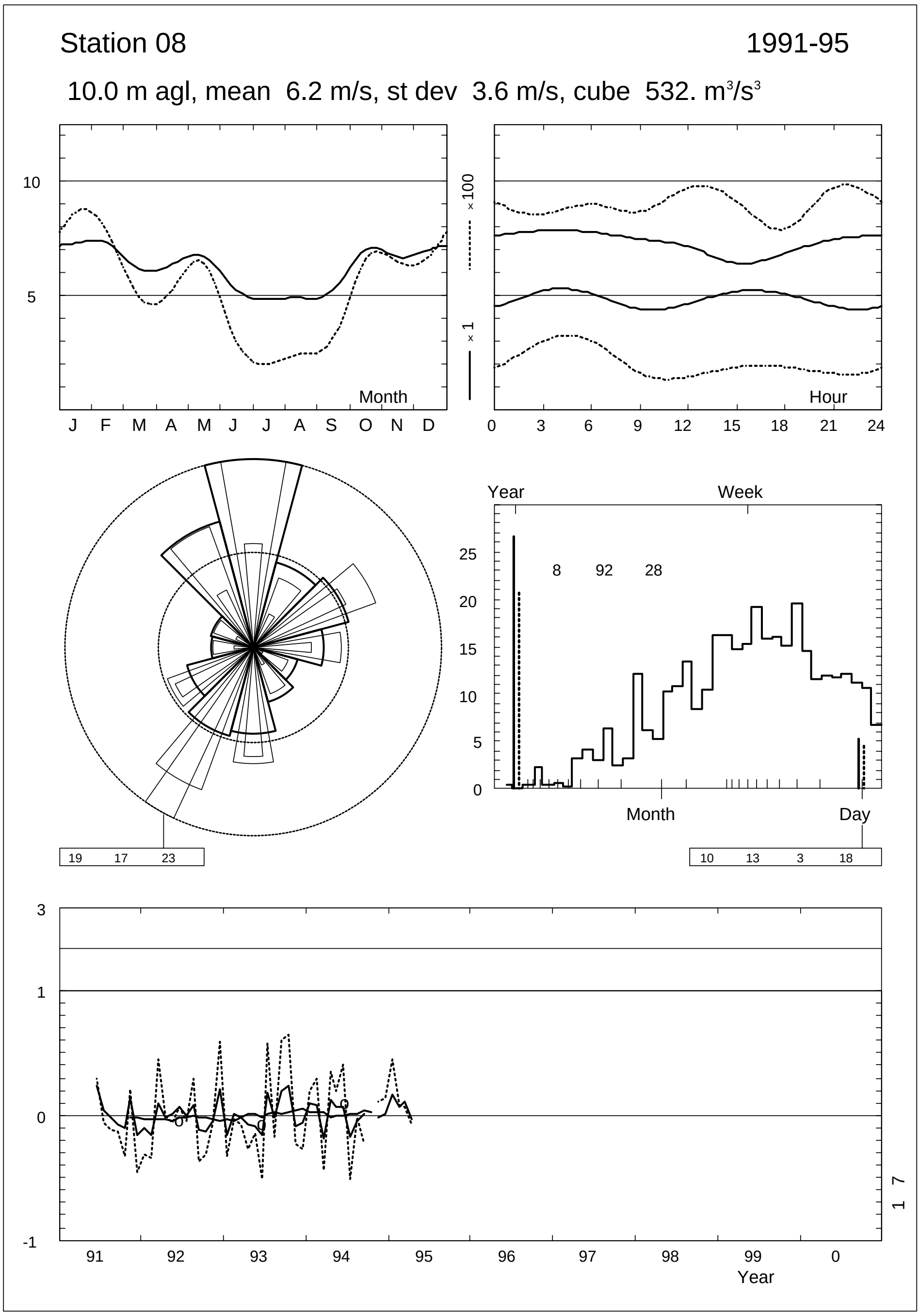
Height of anemometer: 10.0 m a.g.l. 199106271405 – 199504281215

Sect	Freq	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17	A	k
0	18.6	9	66	127	160	154	128	91	72	54	76	35	16	6	4	6.0	1.66
30	8.6	21	137	172	179	147	100	67	47	31	47	27	14	6	4	4.9	1.38
60	9.9	12	55	61	74	86	99	108	108	89	150	93	43	16	5	8.3	2.26
90	6.9	10	37	57	81	104	125	126	115	99	137	70	26	10	2	7.8	2.32
120	4.6	16	68	148	195	190	154	126	57	26	17	1	0	0	0	5.1	2.47
150	5.5	12	64	146	199	180	142	103	54	34	39	18	7	1	0	5.3	1.85
180	8.5	9	38	82	115	106	92	90	77	75	113	83	65	35	18	8.2	1.81
210	9.1	7	24	44	63	75	78	83	82	80	141	114	97	57	53	10.2	2.12
240	6.7	8	36	72	100	106	104	90	86	75	120	91	60	31	20	8.3	1.86
270	4.3	16	70	136	162	144	120	97	78	63	74	29	9	2	0	5.9	1.85
300	4.4	20	82	152	147	122	111	96	94	67	72	25	10	1	0	5.9	1.91
330	12.9	9	62	143	174	137	114	92	77	66	75	34	12	3	0	5.9	1.79
Total	100.0	11	61	110	136	128	113	95	79	64	92	54	31	15	9	6.8	1.65





	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	7.6	7.6	6.1	6.3	6.7	5.3	4.5	4.7	5.0	7.2	6.8	7.2	6.3
1	7.5	7.6	6.4	6.2	6.8	5.3	4.7	4.8	5.1	7.1	6.7	7.1	6.3
2	7.7	7.5	6.4	6.3	7.0	5.4	4.9	5.1	5.1	7.3	6.9	6.9	6.4
3	7.8	7.5	6.6	6.3	6.9	5.5	5.2	4.9	5.2	7.3	7.1	7.1	6.5
4	8.2	7.5	6.8	6.3	6.8	5.6	5.1	5.0	5.2	7.4	7.1	7.4	6.6
5	7.7	7.4	6.6	6.6	6.8	5.8	5.2	4.9	5.2	7.1	6.9	7.3	6.5
6	7.7	7.8	6.6	6.6	6.7	5.8	5.0	5.0	5.3	7.3	7.0	7.4	6.6
7	7.8	7.7	6.7	6.6	6.5	5.6	4.8	5.1	5.3	7.4	6.9	7.3	6.5
8	7.5	7.5	6.2	6.5	6.7	5.4	4.7	4.8	5.1	7.2	6.8	7.3	6.3
9	7.4	7.7	6.2	6.4	6.6	5.2	4.4	4.9	5.1	6.8	6.7	7.1	6.2
10	7.3	7.5	5.8	6.0	6.9	4.9	4.4	4.6	5.0	6.6	6.6	7.1	6.1
11	7.1	7.2	5.7	5.9	7.0	4.9	4.5	4.7	5.2	6.7	6.5	6.9	6.0
12	7.1	7.0	5.9	6.2	7.2	5.0	4.6	4.9	5.4	6.9	6.2	6.8	6.1
13	6.7	6.6	5.9	6.3	7.4	5.0	4.9	5.0	5.5	6.7	6.1	6.7	6.1
14	6.6	6.7	5.8	6.7	7.1	5.2	5.0	5.1	5.6	6.8	6.2	6.5	6.1
15	6.4	6.6	5.7	6.7	7.0	5.2	5.1	5.4	5.6	6.9	6.2	6.4	6.1
16	6.4	6.4	5.7	6.5	7.0	5.3	5.4	5.5	5.5	6.6	6.2	6.4	6.1
17	6.2	6.7	5.9	6.7	6.5	5.6	5.3	5.2	5.4	6.7	6.3	6.5	6.1
18	6.8	6.9	5.7	6.4	6.2	5.3	5.0	4.9	5.1	6.7	6.5	6.9	6.0
19	7.0	7.0	5.7	6.0	5.9	4.8	4.5	4.4	5.1	7.0	6.7	7.0	6.0
20	7.0	7.2	6.0	6.0	5.8	4.6	4.3	4.3	5.1	7.2	6.7	7.1	6.0
21	7.4	7.4	6.0	6.2	6.0	4.8	4.5	4.6	5.0	7.0	6.7	7.3	6.1
22	7.3	7.5	6.2	6.2	6.2	4.8	4.3	4.5	4.8	7.1	6.7	7.3	6.1
23	7.6	7.4	6.5	6.0	6.4	4.9	4.5	4.5	5.1	6.9	6.7	7.3	6.2
Mean	7.2	7.2	6.1	6.3	6.7	5.2	4.8	4.9	5.2	7.0	6.6	7.0	6.2



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1991	—	—	—	—	—	6.5	5.0	4.8	4.8	6.3	7.5	5.9	5.8
1992	6.5	6.1	6.7	6.2	6.8	5.6	4.8	5.3	4.6	6.1	6.4	8.4	6.1
1993	6.1	7.4	6.0	5.8	6.1	4.4	5.6	4.8	6.2	8.6	6.1	6.6	6.1
1994	7.9	7.9	5.0	7.1	7.1	5.5	3.9	4.6	5.3	—	6.5	7.1	6.2
1995	8.5	7.7	6.8	6.1	—	—	—	—	—	—	—	—	7.3
Mean	7.2	7.2	6.1	6.3	6.7	5.2	4.8	4.9	5.2	7.0	6.6	7.0	6.2

Roughness Class 0 ($z_0 = 0.0002$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	4.0	3.4	5.1	8.5	6.7	5.3	5.1	6.2	7.3	7.8	6.8	4.9	5.9
	2.00	1.77	1.95	2.47	2.13	2.03	2.06	2.38	2.33	2.05	2.11	1.96	1.82
25	4.4	3.8	5.6	9.3	7.4	5.8	5.6	6.7	8.0	8.6	7.4	5.4	6.5
	2.06	1.83	2.01	2.55	2.20	2.10	2.13	2.45	2.40	2.11	2.18	2.03	1.87
50	4.7	4.0	6.1	9.9	7.9	6.3	6.1	7.2	8.6	9.2	8.0	5.8	7.0
	2.12	1.88	2.06	2.62	2.26	2.15	2.19	2.52	2.46	2.17	2.24	2.08	1.91
100	5.1	4.4	6.6	10.8	8.6	6.8	6.6	7.8	9.3	9.9	8.6	6.3	7.6
	2.05	1.82	2.00	2.54	2.19	2.09	2.12	2.44	2.38	2.10	2.17	2.01	1.86
200	5.6	4.8	7.2	11.9	9.5	7.5	7.2	8.7	10.3	10.9	9.5	6.9	8.4
	1.94	1.73	1.89	2.40	2.07	1.98	2.00	2.31	2.26	2.00	2.05	1.90	1.78
Freq.	11.4	6.7	8.0	11.1	8.5	6.4	5.2	5.2	6.9	7.6	10.1	12.9	100.0

Roughness Class 1 ($z_0 = 0.0300$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	2.7	2.3	3.8	6.3	4.0	3.6	3.6	4.5	5.2	5.5	4.5	3.2	4.1
	1.73	1.44	1.76	2.26	2.05	1.58	1.81	2.07	1.97	1.69	1.81	1.70	1.60
25	3.2	2.8	4.6	7.6	4.8	4.3	4.3	5.4	6.3	6.5	5.4	3.8	5.0
	1.87	1.55	1.90	2.43	2.21	1.71	1.96	2.23	2.12	1.80	1.96	1.83	1.69
50	3.8	3.2	5.3	8.7	5.6	5.0	5.0	6.2	7.2	7.5	6.2	4.4	5.8
	2.10	1.74	2.14	2.72	2.48	1.92	2.20	2.51	2.38	1.99	2.20	2.06	1.85
100	4.4	3.9	6.3	10.3	6.6	6.0	6.0	7.4	8.6	8.8	7.4	5.3	6.8
	2.23	1.85	2.28	2.90	2.64	2.04	2.34	2.67	2.54	2.13	2.34	2.19	1.94
200	5.5	4.8	7.9	12.7	8.2	7.4	7.4	9.2	10.7	10.8	9.2	6.5	8.5
	2.13	1.77	2.17	2.77	2.53	1.95	2.24	2.55	2.43	2.04	2.24	2.09	1.89
Freq.	10.4	5.3	8.8	11.8	7.5	6.2	4.8	5.2	7.5	7.7	11.1	13.8	100.0

Roughness Class 2 ($z_0 = 0.1000$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	2.3	2.1	3.5	5.4	3.4	3.1	3.2	4.0	4.6	4.7	3.8	2.8	3.6
	1.66	1.35	1.73	2.20	2.07	1.57	1.84	2.06	1.94	1.69	1.78	1.76	1.60
25	2.9	2.6	4.4	6.7	4.2	3.8	4.0	4.9	5.7	5.8	4.7	3.4	4.5
	1.77	1.44	1.85	2.35	2.22	1.67	1.97	2.20	2.08	1.79	1.90	1.88	1.69
50	3.4	3.1	5.1	7.8	4.9	4.5	4.7	5.8	6.6	6.8	5.5	4.0	5.3
	1.96	1.59	2.05	2.59	2.45	1.85	2.18	2.44	2.30	1.96	2.11	2.08	1.82
100	4.0	3.7	6.1	9.3	5.9	5.4	5.6	6.9	7.9	8.0	6.5	4.8	6.3
	2.15	1.75	2.25	2.85	2.69	2.03	2.39	2.69	2.53	2.16	2.31	2.28	1.96
200	4.9	4.6	7.6	11.4	7.3	6.7	6.9	8.5	9.7	9.8	8.1	5.9	7.7
	2.06	1.67	2.15	2.73	2.58	1.95	2.29	2.57	2.42	2.07	2.22	2.19	1.90
Freq.	9.9	5.6	8.8	11.8	7.4	5.9	4.8	5.4	7.3	8.1	11.7	13.3	100.0

Roughness Class 3 ($z_0 = 0.4000$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	1.9	1.9	3.1	4.1	2.7	2.5	2.7	3.2	3.6	3.6	2.8	2.1	2.9
	1.74	1.46	1.76	2.13	2.06	1.64	1.90	2.00	1.92	1.69	1.74	1.68	1.62
25	2.5	2.5	4.0	5.4	3.5	3.3	3.5	4.2	4.8	4.7	3.8	2.8	3.8
	1.84	1.55	1.87	2.25	2.18	1.74	2.01	2.12	2.04	1.79	1.84	1.77	1.70
50	3.0	3.1	4.9	6.6	4.3	4.0	4.2	5.1	5.8	5.7	4.6	3.4	4.6
	2.00	1.68	2.03	2.45	2.37	1.89	2.18	2.30	2.22	1.94	2.00	1.93	1.82
100	3.6	3.8	5.9	7.9	5.2	4.8	5.1	6.1	6.9	6.9	5.5	4.1	5.5
	2.28	1.91	2.31	2.79	2.70	2.15	2.49	2.62	2.53	2.20	2.28	2.20	2.01
200	4.4	4.6	7.2	9.6	6.3	5.9	6.2	7.5	8.5	8.4	6.7	5.0	6.7
	2.20	1.85	2.23	2.69	2.60	2.08	2.40	2.53	2.43	2.13	2.20	2.12	1.96
Freq.	9.2	6.0	9.0	11.3	7.2	5.7	4.9	5.7	7.3	8.6	12.1	12.9	100.0

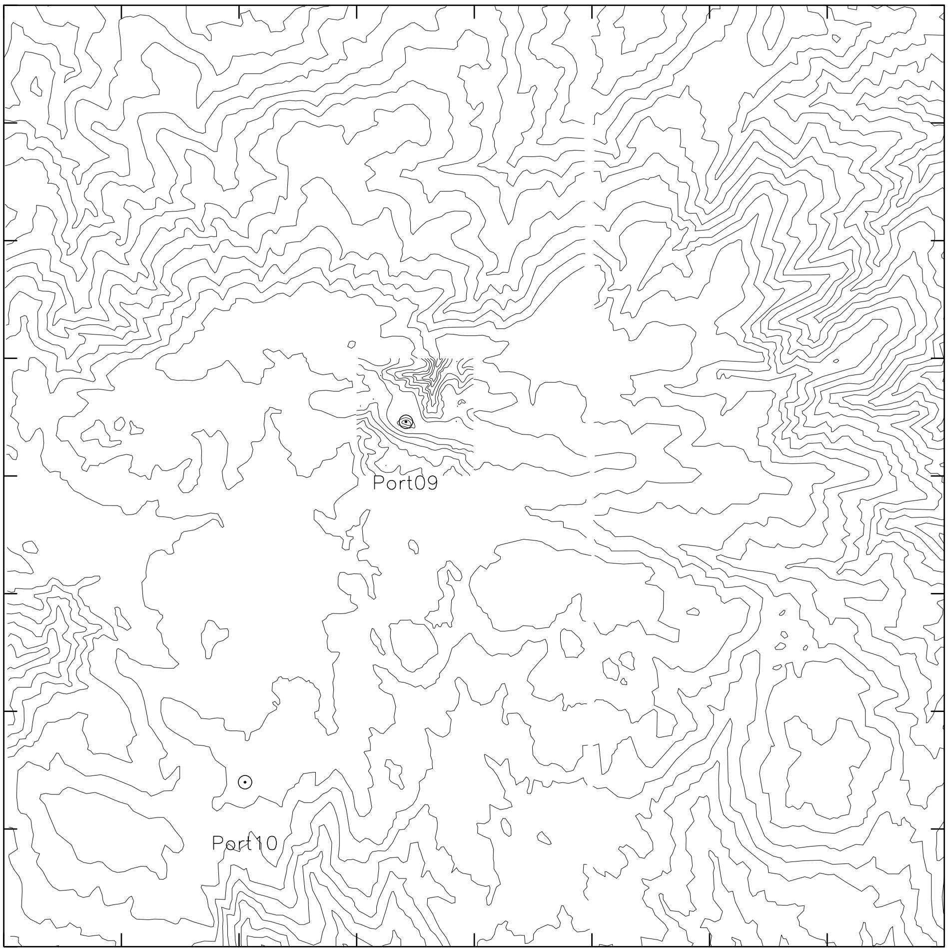
z	Class 0		Class 1		Class 2		Class 3	
m	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}
10	5.3	190	3.7	77	3.2	50	2.6	24
25	5.8	242	4.4	122	4.0	89	3.4	53
50	6.2	294	5.1	170	4.7	131	4.1	86
100	6.7	384	6.1	268	5.6	204	4.9	136
200	7.4	545	7.5	526	6.8	394	6.0	255

Station 09 (Adaufe) Portugal

$40^\circ\ 52'\ 37''$ N	$08^\circ\ 14'\ 50''$ W	UTM 29	E 563 421 m	N 4 525 458 m	1082 m

The mast is situated in the Serra da Freita mountains, about 2 km SSW of the village of Adaufe. The surface consists of a fairly homogeneous cover of very low bushes and some rocks and bare soil. There are no houses or other obstacles close to the mast.

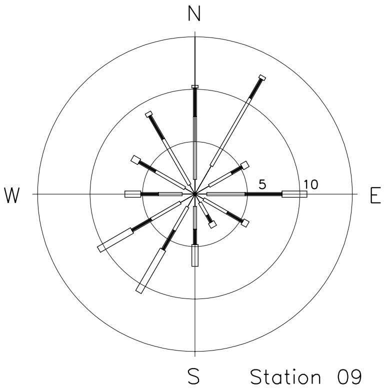
On the map below, the height contour interval is 50 m and 10 m, respectively, and tick marks are shown for every kilometer.

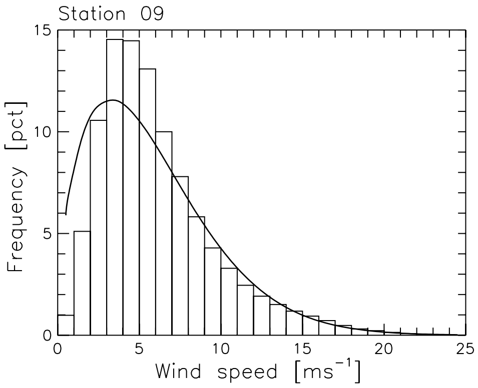


Sector	Input		Obstacles		Roughness		Orography		z_{0m}
0	0.0	0.0	0.0	0.0	0.0	0.0	74.0	8.0	0.0300
30	0.0	0.0	0.0	0.0	0.0	0.0	85.4	−0.5	0.0300
60	0.0	0.0	0.0	0.0	0.0	0.0	71.6	−8.6	0.0300
90	0.0	0.0	0.0	0.0	0.0	0.0	43.0	−9.7	0.0300
120	0.0	0.0	0.0	0.0	0.0	0.0	27.9	0.7	0.0300
150	0.0	0.0	0.0	0.0	0.0	0.0	45.9	10.1	0.0300
180	0.0	0.0	0.0	0.0	0.0	0.0	74.0	8.0	0.0300
210	0.0	0.0	0.0	0.0	0.0	0.0	85.4	−0.5	0.0300
240	0.0	0.0	0.0	0.0	0.0	0.0	71.6	−8.6	0.0300
270	0.0	0.0	0.0	0.0	0.0	0.0	43.0	−9.7	0.0300
300	0.0	0.0	0.0	0.0	0.0	0.0	27.9	0.7	0.0300
330	0.0	0.0	0.0	0.0	0.0	0.0	45.9	10.1	0.0300

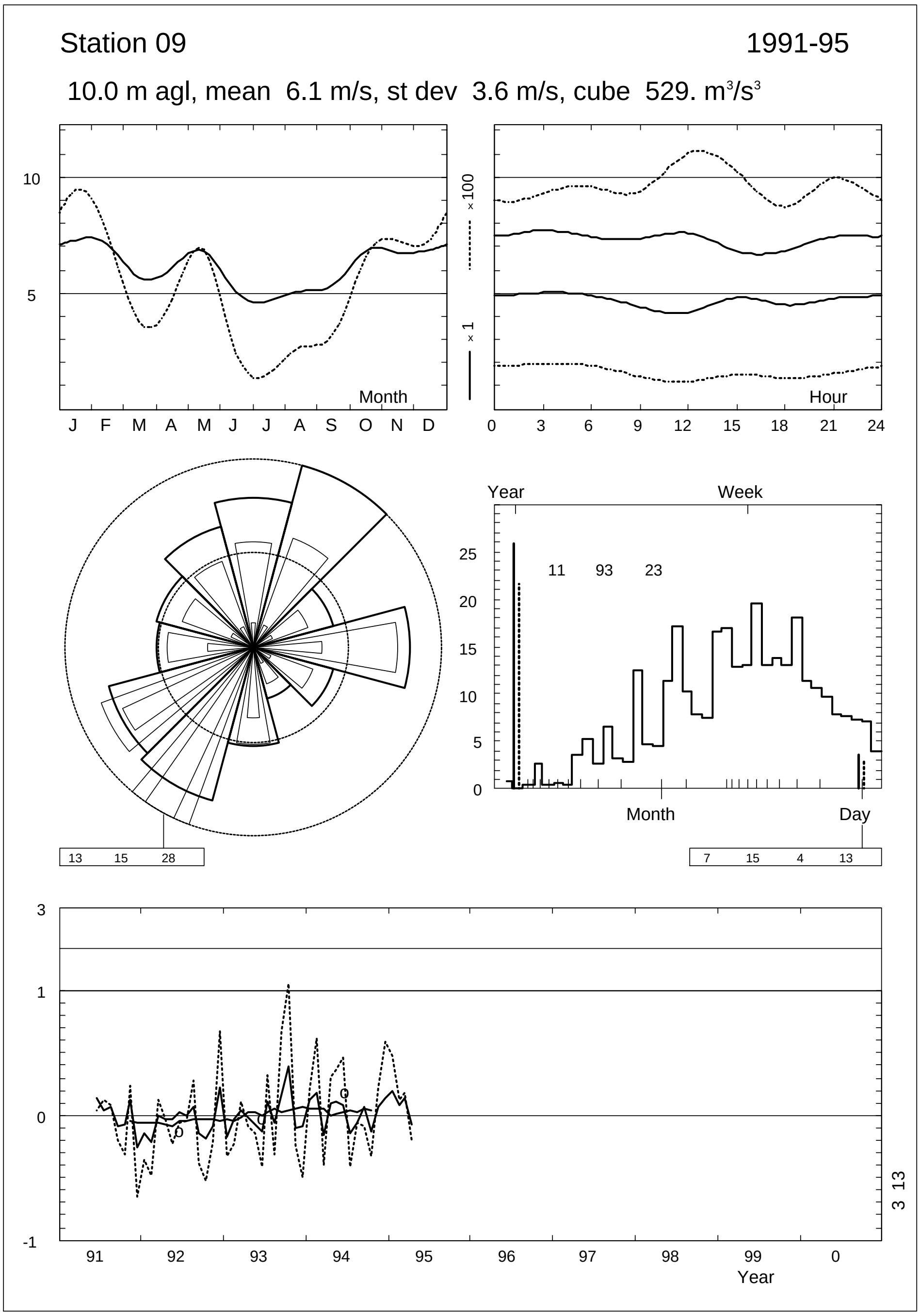
Height of anemometer: 10.0 m a.g.l. 199106271045 – 199504281145

Sect	Freq	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17	A	k
0	10.4	5	35	96	170	206	203	135	83	43	22	3	0	0	0	5.6	2.79
30	13.0	9	63	168	233	195	147	85	52	25	17	4	2	1	0	4.9	2.11
60	5.8	17	88	165	166	142	117	84	67	48	60	27	12	6	0	5.5	1.63
90	10.7	5	30	70	97	115	131	125	110	93	135	59	21	7	1	7.5	2.29
120	5.8	11	50	104	137	152	157	125	96	72	74	17	3	0	0	6.2	2.31
150	3.6	22	92	146	162	127	98	76	68	67	79	35	19	7	1	5.8	1.60
180	6.9	14	60	95	109	112	96	79	69	64	105	88	48	37	24	7.8	1.66
210	10.8	10	46	75	86	82	71	65	69	62	115	103	89	68	59	9.8	1.89
240	10.6	9	51	91	112	101	90	77	65	57	102	85	68	42	47	8.4	1.61
270	6.7	14	67	101	125	111	104	97	80	73	113	66	33	11	4	7.1	1.85
300	6.9	10	46	106	187	160	123	104	88	68	77	23	7	1	0	6.0	1.98
330	9.0	6	29	80	154	205	201	139	94	50	33	7	1	0	0	5.9	2.66
Total	100.0	10	51	106	145	145	131	100	78	58	76	44	27	17	13	6.5	1.54





	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	7.4	7.6	5.8	6.2	6.6	4.8	4.9	5.0	5.1	6.9	7.1	6.9	6.2
1	7.4	7.6	5.9	6.3	6.7	4.9	5.0	5.1	5.3	7.0	7.1	7.1	6.3
2	7.6	7.5	6.0	6.2	7.0	5.0	5.0	5.2	5.2	7.1	6.9	7.0	6.3
3	7.7	7.4	5.9	6.3	7.0	5.3	5.0	5.3	5.3	7.0	7.1	7.0	6.4
4	7.6	7.1	6.0	6.3	7.0	5.2	4.9	5.2	5.4	7.2	6.9	7.1	6.3
5	7.6	7.2	5.9	6.3	6.8	5.2	4.8	5.0	5.4	7.1	6.9	6.9	6.3
6	7.4	7.0	5.9	6.2	6.8	5.4	4.9	5.0	5.5	7.0	7.0	6.8	6.2
7	7.4	7.2	5.9	6.2	6.8	5.4	4.6	4.9	5.4	6.9	6.7	7.1	6.2
8	7.4	7.3	5.7	6.3	7.1	5.4	4.5	4.8	5.4	6.8	6.6	6.9	6.2
9	7.3	7.2	5.8	6.2	7.2	5.4	4.4	4.9	5.3	6.9	6.6	6.9	6.2
10	7.4	7.4	5.7	6.0	7.0	5.2	4.2	4.9	5.3	7.0	6.9	6.8	6.1
11	7.5	7.3	5.6	5.7	7.0	4.9	4.1	4.9	5.2	6.9	6.9	6.8	6.1
12	7.6	7.3	5.4	5.9	7.3	4.8	4.2	4.8	5.2	6.8	6.7	6.9	6.1
13	7.3	6.9	5.2	5.9	7.3	4.9	4.2	5.1	5.4	6.6	6.6	7.0	6.0
14	7.1	6.8	5.4	6.3	7.5	5.1	4.6	5.2	5.6	6.6	6.5	6.9	6.1
15	6.8	6.6	5.5	6.4	7.2	5.3	4.8	5.4	5.8	6.6	6.5	6.7	6.1
16	6.5	6.5	5.5	6.4	7.1	5.3	4.8	5.5	5.8	6.3	6.3	6.4	6.0
17	6.4	6.4	5.5	6.3	6.8	5.2	4.8	5.5	5.6	6.4	6.4	6.6	6.0
18	6.8	6.7	5.2	6.0	6.3	5.1	4.5	5.3	5.5	6.4	6.5	6.6	5.9
19	7.0	6.9	5.4	5.8	6.0	4.6	4.4	5.0	5.5	6.6	6.7	6.9	5.9
20	7.3	7.0	5.7	5.9	6.0	4.8	4.7	5.0	5.4	6.8	6.8	7.1	6.1
21	7.4	7.1	5.7	5.9	5.9	4.9	4.8	4.9	5.2	6.9	6.9	6.9	6.1
22	7.3	7.3	5.7	5.8	6.3	4.8	4.8	4.8	5.1	7.0	6.6	6.9	6.0
23	7.3	7.4	5.8	5.9	6.5	4.8	4.8	4.9	5.2	6.8	6.8	6.8	6.1
Mean	7.3	7.1	5.7	6.1	6.8	5.1	4.7	5.1	5.4	6.8	6.8	6.9	6.1



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1991	—	—	—	—	—	5.8	4.9	5.4	4.9	6.3	7.6	5.1	5.7
1992	6.2	5.6	5.6	6.0	6.6	5.2	4.6	5.4	4.6	5.6	6.2	8.4	5.8
1993	6.0	6.9	5.9	6.0	6.3	4.4	5.1	4.8	6.3	9.5	6.1	6.3	6.1
1994	8.1	8.4	4.7	6.7	7.5	5.5	4.0	4.7	5.8	5.9	7.2	7.8	6.3
1995	8.7	7.7	6.4	5.7	—	—	—	—	—	—	—	—	7.2
Mean	7.3	7.1	5.7	6.1	6.8	5.1	4.7	5.1	5.4	6.8	6.8	6.9	6.1

Roughness Class 0 ($z_0 = 0.0002$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	4.8	4.0	4.2	6.9	7.2	6.9	6.8	7.5	7.4	7.6	7.0	5.9	6.3
	2.96	2.63	2.05	2.41	2.56	2.07	1.99	2.21	2.02	1.96	2.19	2.67	1.97
25	5.3	4.3	4.6	7.5	7.9	7.5	7.5	8.2	8.1	8.3	7.7	6.4	6.9
	3.05	2.72	2.11	2.49	2.64	2.13	2.05	2.28	2.08	2.02	2.26	2.75	2.03
50	5.7	4.6	4.9	8.1	8.4	8.1	8.1	8.8	8.8	8.9	8.2	6.9	7.4
	3.13	2.79	2.17	2.55	2.71	2.19	2.11	2.34	2.14	2.08	2.32	2.83	2.07
100	6.1	5.0	5.3	8.7	9.2	8.8	8.7	9.6	9.5	9.6	8.9	7.5	8.1
	3.03	2.70	2.10	2.47	2.62	2.12	2.04	2.27	2.07	2.01	2.25	2.74	2.02
200	6.8	5.6	5.9	9.7	10.1	9.7	9.6	10.6	10.5	10.6	9.9	8.3	8.9
	2.87	2.56	1.99	2.34	2.48	2.01	1.93	2.15	1.96	1.92	2.13	2.59	1.93
Freq.	9.3	9.2	6.9	9.6	8.7	5.8	5.9	7.5	8.6	8.8	9.3	10.3	100.0

Roughness Class 1 ($z_0 = 0.0300$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	3.2	2.7	3.1	5.1	5.1	4.6	4.8	5.3	5.1	5.3	4.8	4.0	4.4
	2.55	2.15	1.69	2.17	2.17	1.56	1.69	1.89	1.66	1.67	1.98	2.61	1.71
25	3.8	3.2	3.7	6.1	6.0	5.5	5.7	6.4	6.1	6.3	5.7	4.8	5.3
	2.76	2.32	1.83	2.35	2.35	1.68	1.82	2.05	1.79	1.78	2.14	2.81	1.83
50	4.4	3.7	4.3	7.0	7.0	6.4	6.7	7.4	7.1	7.3	6.6	5.5	6.1
	3.10	2.61	2.05	2.64	2.64	1.89	2.05	2.30	2.01	1.98	2.40	3.17	2.02
100	5.2	4.4	5.1	8.3	8.3	7.6	7.9	8.7	8.4	8.6	7.8	6.5	7.3
	3.30	2.78	2.19	2.81	2.81	2.01	2.18	2.45	2.14	2.12	2.56	3.37	2.13
200	6.4	5.5	6.4	10.3	10.3	9.4	9.8	10.9	10.5	10.6	9.8	8.1	9.0
	3.15	2.65	2.09	2.69	2.69	1.92	2.08	2.33	2.05	2.03	2.44	3.22	2.05
Freq.	9.0	9.3	5.9	10.8	8.0	5.2	6.2	7.8	8.9	8.9	9.4	10.7	100.0

Roughness Class 2 ($z_0 = 0.1000$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	2.7	2.4	2.9	4.4	4.4	4.0	4.2	4.6	4.4	4.6	4.1	3.4	3.8
	2.57	2.05	1.65	2.17	2.10	1.58	1.71	1.86	1.65	1.67	1.98	2.60	1.71
25	3.4	2.9	3.6	5.4	5.4	4.9	5.2	5.7	5.5	5.7	5.1	4.2	4.7
	2.75	2.19	1.77	2.32	2.25	1.69	1.83	1.99	1.76	1.79	2.12	2.78	1.81
50	3.9	3.4	4.3	6.4	6.3	5.8	6.1	6.7	6.5	6.6	5.9	4.9	5.6
	3.05	2.42	1.96	2.57	2.49	1.87	2.03	2.20	1.95	1.96	2.35	3.08	1.97
100	4.7	4.1	5.1	7.6	7.5	7.0	7.3	7.9	7.7	7.9	7.1	5.8	6.7
	3.35	2.66	2.15	2.82	2.74	2.05	2.23	2.42	2.14	2.16	2.58	3.38	2.14
200	5.8	5.0	6.3	9.4	9.3	8.6	9.0	9.8	9.5	9.7	8.7	7.2	8.2
	3.20	2.55	2.06	2.70	2.62	1.96	2.13	2.31	2.05	2.07	2.47	3.24	2.06
Freq.	9.0	8.9	6.3	10.5	7.9	5.2	6.3	7.9	8.8	8.9	9.7	10.5	100.0

Roughness Class 3 ($z_0 = 0.4000$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	2.1	1.9	2.5	3.5	3.4	3.2	3.3	3.6	3.5	3.6	3.1	2.7	3.0
	2.33	2.01	1.71	2.17	2.06	1.59	1.72	1.83	1.67	1.71	1.97	2.63	1.71
25	2.8	2.5	3.4	4.6	4.5	4.2	4.4	4.7	4.7	4.7	4.1	3.5	4.0
	2.47	2.13	1.81	2.30	2.19	1.69	1.83	1.94	1.77	1.81	2.09	2.79	1.81
50	3.3	3.0	4.1	5.5	5.4	5.1	5.3	5.7	5.6	5.7	5.0	4.2	4.8
	2.69	2.31	1.96	2.50	2.38	1.83	1.98	2.10	1.92	1.96	2.27	3.03	1.94
100	4.0	3.7	4.9	6.6	6.5	6.1	6.4	6.9	6.8	6.9	6.0	5.1	5.8
	3.06	2.63	2.23	2.85	2.71	2.08	2.26	2.40	2.19	2.23	2.58	3.45	2.17
200	4.9	4.5	6.0	8.1	8.0	7.5	7.9	8.4	8.3	8.4	7.3	6.2	7.1
	2.95	2.54	2.15	2.74	2.61	2.01	2.17	2.31	2.11	2.15	2.49	3.33	2.10
Freq.	9.1	8.4	6.8	10.2	7.5	5.4	6.6	8.0	8.8	9.0	9.9	10.3	100.0

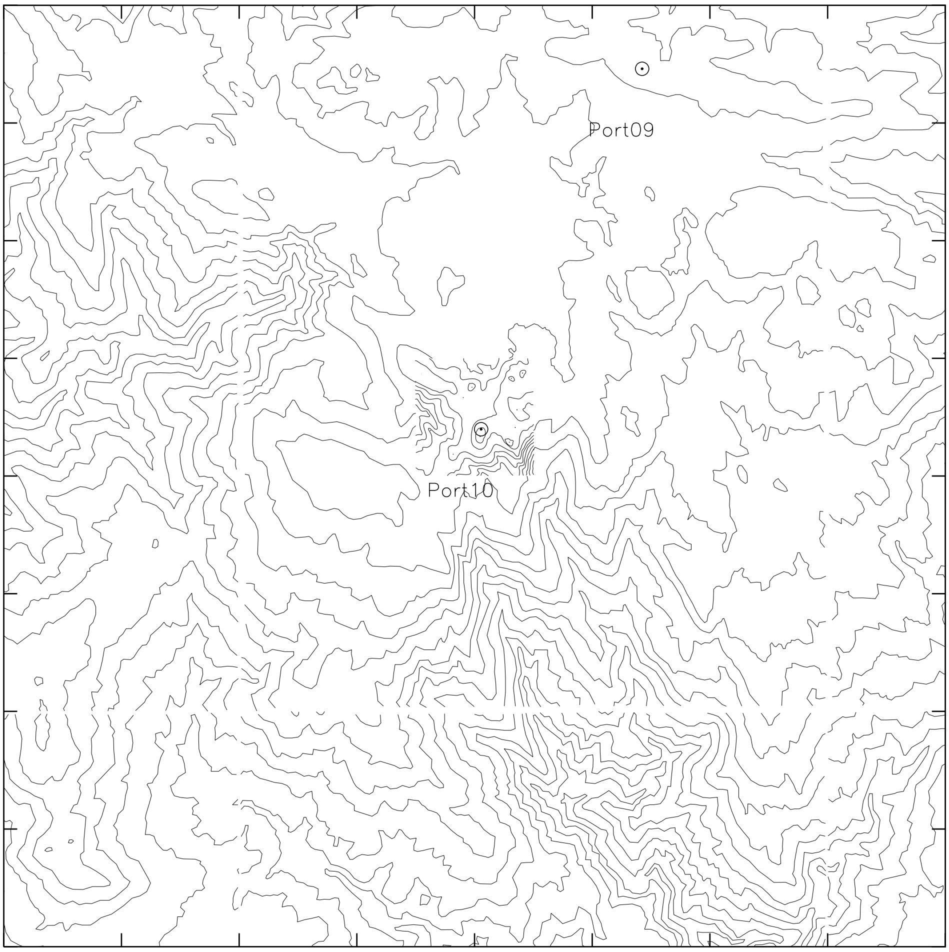
z	Class 0		Class 1		Class 2		Class 3	
m	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}
10	5.6	208	3.9	84	3.4	55	2.7	27
25	6.1	266	4.7	132	4.2	97	3.5	58
50	6.6	323	5.4	185	4.9	142	4.3	94
100	7.1	422	6.4	294	5.9	224	5.2	149
200	7.9	597	8.0	582	7.3	434	6.3	279

Station 10 (Castanheira) Portugal

$40^\circ\ 50'\ 58''$ N	$08^\circ\ 15'\ 50''$ W	UTM 29	E 562 053 m	N 4 522 395 m	1012 m

The mast is situated just south of the Serra da Freita mountains, about 1.5 km ESE of the village of Castanheira. The surface consists of a fairly homogeneous cover of very low bushes and some rocks and bare soil. There are no houses or other obstacles close to the mast.

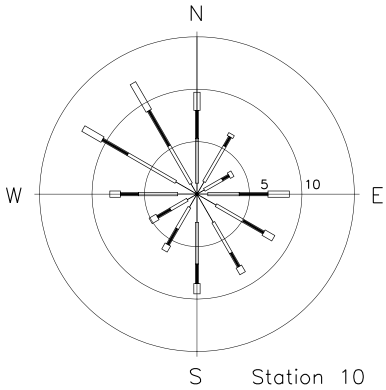
On the map below, the height contour interval is 50 m and 10 m, respectively, and tick marks are shown for every kilometer.

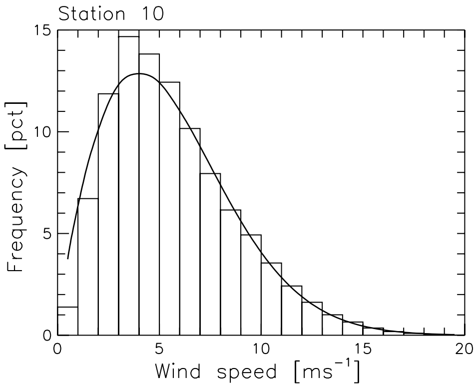


Sector	Input		Obstacles		Roughness		Orography		z_{0m}
0	0.0	0.0	0.0	0.0	0.0	0.0	50.9	−10.5	0.0300
30	0.0	0.0	0.0	0.0	0.0	0.0	22.1	−10.1	0.0300
60	0.0	0.0	0.0	0.0	0.0	0.0	11.3	3.0	0.0300
90	0.0	0.0	0.0	0.0	0.0	0.0	33.2	11.9	0.0300
120	0.0	0.0	0.0	0.0	0.0	0.0	60.1	7.7	0.0300
150	0.0	0.0	0.0	0.0	0.0	0.0	67.7	−2.0	0.0300
180	0.0	0.0	0.0	0.0	0.0	0.0	50.9	−10.5	0.0300
210	0.0	0.0	0.0	0.0	0.0	0.0	22.1	−10.1	0.0300
240	0.0	0.0	0.0	0.0	0.0	0.0	11.3	3.0	0.0300
270	0.0	0.0	0.0	0.0	0.0	0.0	33.2	11.9	0.0300
300	0.0	0.0	0.0	0.0	0.0	0.0	60.1	7.7	0.0300
330	0.0	0.0	0.0	0.0	0.0	0.0	67.7	−2.0	0.0300

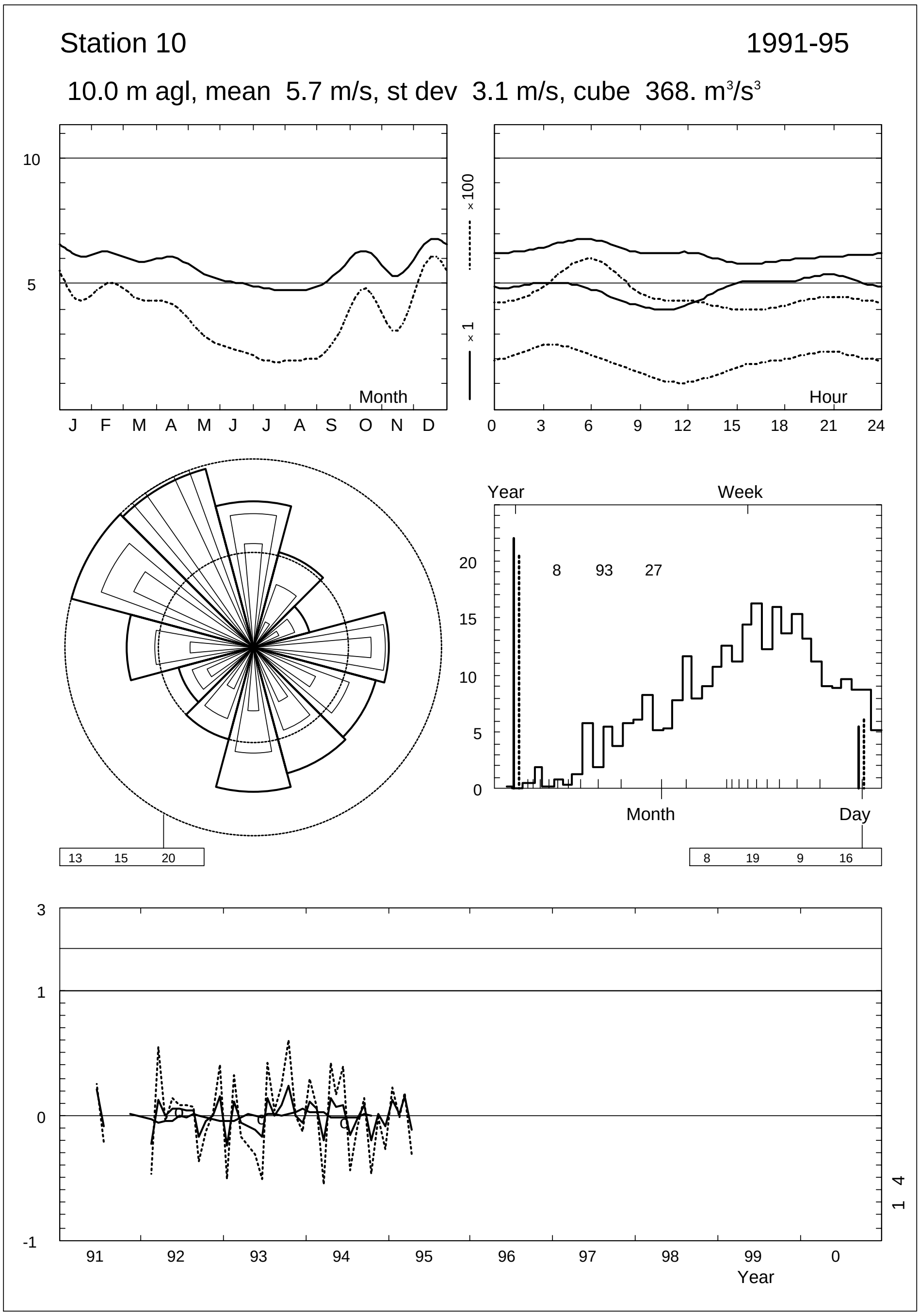
Height of anemometer: 10.0 m a.g.l. 199106261625 – 199504141235

Sect	Freq	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17	A	k
0	9.7	6	28	73	129	157	155	115	89	70	101	52	18	5	1	6.8	1.95
30	6.6	16	47	143	227	222	144	82	42	31	32	11	3	1	0	5.0	1.93
60	3.9	22	61	125	199	180	127	82	62	43	52	27	12	7	1	5.4	1.58
90	8.8	12	44	62	96	115	129	119	105	87	133	68	23	7	1	7.5	2.22
120	8.4	18	91	140	136	113	109	107	86	71	89	30	7	2	0	6.1	1.97
150	8.7	20	140	196	167	122	99	84	54	33	35	24	16	6	3	4.9	1.42
180	9.5	15	95	174	175	133	108	84	63	49	68	25	8	3	0	5.3	1.64
210	6.2	15	75	142	135	125	120	113	101	67	76	25	5	0	0	6.1	2.10
240	5.1	17	70	121	139	116	110	110	99	70	93	37	15	4	1	6.5	1.98
270	8.3	16	77	128	168	150	131	94	62	52	75	32	12	3	0	5.8	1.75
300	12.5	13	63	110	153	142	126	92	71	59	92	47	23	7	0	6.3	1.72
330	12.2	7	30	57	96	118	128	123	107	85	122	70	36	13	7	7.7	2.06
Total	100.0	14	67	119	147	138	124	102	79	62	85	40	17	5	1	6.2	1.81





	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	6.2	6.8	5.9	6.1	5.2	5.1	4.9	4.7	5.3	6.5	5.4	6.7	5.7
1	6.2	6.8	5.9	6.2	5.2	5.0	5.1	5.0	5.3	6.4	5.3	6.7	5.8
2	6.1	6.7	6.2	6.3	5.2	5.2	5.3	5.0	5.3	6.6	5.6	6.7	5.9
3	6.5	6.6	6.1	6.5	5.4	5.3	5.0	5.2	5.4	6.6	5.7	6.7	5.9
4	6.7	6.3	6.1	6.4	5.4	5.3	5.0	4.9	5.3	6.5	5.5	7.0	5.9
5	6.4	6.2	6.2	6.3	5.4	5.2	5.1	4.7	5.3	6.4	5.7	6.8	5.8
6	6.8	6.5	6.0	6.2	5.2	5.4	4.8	4.7	5.1	6.3	5.6	6.7	5.8
7	6.4	6.4	6.1	6.2	5.3	5.2	4.5	4.5	5.3	6.4	5.6	6.7	5.7
8	6.3	6.5	5.7	6.2	5.6	5.0	4.3	4.4	5.1	6.3	5.4	6.7	5.6
9	6.2	6.2	5.9	6.0	5.5	5.0	4.1	4.4	4.9	6.2	5.3	6.8	5.5
10	6.1	6.2	5.9	5.6	5.3	4.6	3.9	4.1	4.8	6.2	5.4	7.0	5.4
11	6.2	6.1	5.6	5.4	5.5	4.4	4.0	4.2	4.9	6.3	5.3	6.9	5.4
12	6.2	6.2	5.4	5.5	5.6	4.5	4.2	4.2	4.9	6.2	5.1	7.0	5.4
13	6.1	5.9	5.4	5.6	5.6	4.7	4.2	4.6	5.0	6.1	5.1	6.9	5.4
14	6.0	5.9	5.6	5.9	5.7	4.9	4.7	4.9	5.3	6.0	5.0	6.6	5.6
15	5.8	5.8	5.7	6.3	5.8	5.2	5.0	5.2	5.6	6.1	5.1	6.4	5.7
16	5.7	5.8	5.8	6.4	5.8	5.4	5.2	5.3	5.7	6.0	4.9	6.4	5.7
17	5.6	5.6	5.9	6.3	5.7	5.4	5.2	5.2	5.6	6.3	4.9	6.4	5.7
18	5.9	5.7	5.5	6.0	5.3	5.3	5.1	4.7	5.3	6.1	5.0	6.5	5.5
19	5.9	6.2	5.7	5.9	5.0	4.9	5.0	4.7	5.5	6.3	5.1	6.8	5.6
20	5.9	6.3	6.0	6.1	5.1	4.8	5.2	4.9	5.4	6.6	5.3	6.9	5.7
21	6.1	6.4	6.1	6.1	4.9	5.1	5.3	4.9	5.5	6.4	5.5	6.9	5.8
22	6.0	6.5	6.2	5.9	5.1	5.1	5.2	4.7	5.5	6.5	5.2	6.9	5.8
23	5.9	6.7	6.0	5.8	5.1	5.1	5.0	4.6	5.4	6.0	5.3	6.8	5.7
Mean	6.1	6.3	5.9	6.1	5.4	5.0	4.8	4.7	5.3	6.3	5.3	6.7	5.7



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1991	—	—	—	—	—	6.1	4.4	—	—	—	—	—	4.9
1992	—	4.9	6.6	6.0	5.7	5.3	5.0	4.9	4.4	6.0	5.3	7.7	5.6
1993	4.7	7.0	5.5	5.5	4.8	4.2	5.5	4.7	5.7	7.8	5.3	6.3	5.6
1994	6.8	6.6	4.7	6.9	5.7	5.5	4.1	4.6	5.7	5.1	5.4	6.2	5.6
1995	6.9	6.4	6.7	5.3	—	—	—	—	—	—	—	—	6.5
Mean	6.1	6.3	5.9	6.1	5.4	5.0	4.8	4.7	5.3	6.3	5.3	6.7	5.7

Roughness Class 0 ($z_0 = 0.0002$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	6.7	6.6	7.4	7.7	6.1	4.6	4.9	6.4	7.8	6.8	6.0	6.4	6.5
	2.38	2.17	2.00	2.44	2.22	1.79	1.85	2.13	2.24	2.06	2.07	2.36	2.05
25	7.3	7.3	8.1	8.5	6.7	5.0	5.4	7.1	8.5	7.4	6.5	7.0	7.1
	2.45	2.24	2.06	2.51	2.30	1.85	1.91	2.20	2.31	2.12	2.13	2.44	2.11
50	7.9	7.8	8.7	9.1	7.2	5.4	5.8	7.6	9.1	8.0	7.0	7.5	7.7
	2.52	2.30	2.12	2.58	2.36	1.90	1.96	2.26	2.37	2.18	2.19	2.50	2.16
100	8.5	8.5	9.4	9.9	7.8	5.8	6.3	8.2	9.9	8.6	7.6	8.2	8.3
	2.44	2.23	2.05	2.50	2.28	1.84	1.90	2.19	2.29	2.11	2.12	2.42	2.10
200	9.4	9.4	10.4	10.9	8.6	6.4	6.9	9.1	10.9	9.5	8.4	9.1	9.2
	2.31	2.11	1.94	2.37	2.16	1.74	1.79	2.07	2.17	1.99	2.01	2.30	2.00
Freq.	8.8	9.0	7.4	8.8	7.2	6.2	7.5	8.5	8.1	9.8	9.9	8.8	100.0

Roughness Class 1 ($z_0 = 0.0300$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	4.7	4.6	5.4	5.3	3.7	3.0	3.5	4.8	5.6	4.5	4.1	4.6	4.5
	1.98	1.79	1.71	2.12	1.86	1.44	1.60	1.91	1.90	1.73	1.78	2.06	1.75
25	5.6	5.5	6.4	6.4	4.5	3.6	4.2	5.7	6.7	5.4	4.9	5.5	5.4
	2.13	1.93	1.83	2.29	2.01	1.55	1.73	2.06	2.05	1.87	1.92	2.22	1.88
50	6.5	6.4	7.4	7.4	5.2	4.2	4.9	6.6	7.8	6.3	5.7	6.4	6.3
	2.40	2.17	2.04	2.58	2.26	1.74	1.94	2.31	2.31	2.10	2.16	2.50	2.09
100	7.7	7.6	8.8	8.8	6.2	5.0	5.9	7.9	9.2	7.4	6.7	7.6	7.5
	2.55	2.31	2.18	2.74	2.40	1.85	2.07	2.46	2.45	2.23	2.30	2.67	2.21
200	9.6	9.4	10.8	10.9	7.7	6.2	7.3	9.8	11.5	9.3	8.4	9.4	9.3
	2.44	2.20	2.09	2.62	2.30	1.77	1.98	2.35	2.35	2.13	2.20	2.55	2.12
Freq.	8.9	9.1	6.8	9.5	6.5	6.0	8.0	8.6	7.9	10.5	9.6	8.4	100.0

Roughness Class 2 ($z_0 = 0.1000$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	4.1	4.1	4.7	4.6	3.2	2.7	3.2	4.2	4.8	3.9	3.6	4.1	4.0
	1.98	1.79	1.76	2.08	1.82	1.48	1.60	1.91	1.87	1.74	1.83	2.06	1.76
25	5.1	5.0	5.8	5.6	4.0	3.3	3.9	5.2	5.9	4.8	4.5	5.0	4.9
	2.12	1.91	1.88	2.22	1.95	1.58	1.71	2.04	1.99	1.87	1.95	2.20	1.87
50	5.9	5.9	6.8	6.6	4.7	3.9	4.6	6.1	6.9	5.7	5.3	5.9	5.8
	2.35	2.12	2.08	2.46	2.15	1.74	1.89	2.26	2.21	2.06	2.16	2.44	2.06
100	7.1	7.0	8.1	7.9	5.5	4.7	5.5	7.3	8.3	6.8	6.3	7.0	6.9
	2.58	2.33	2.28	2.70	2.37	1.92	2.08	2.48	2.43	2.27	2.37	2.69	2.24
200	8.7	8.7	10.0	9.7	6.8	5.8	6.8	9.0	10.2	8.4	7.7	8.6	8.5
	2.47	2.22	2.19	2.59	2.26	1.83	1.99	2.38	2.32	2.17	2.27	2.57	2.15
Freq.	8.8	8.9	7.2	9.2	6.5	6.2	7.9	8.6	8.3	10.4	9.5	8.5	100.0

Roughness Class 3 ($z_0 = 0.4000$ m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	3.2	3.2	3.7	3.5	2.5	2.1	2.6	3.4	3.6	3.0	2.9	3.2	3.1
	1.93	1.73	1.83	2.03	1.74	1.45	1.67	1.89	1.83	1.74	1.89	2.04	1.76
25	4.2	4.2	4.9	4.6	3.2	2.8	3.5	4.5	4.8	4.0	3.8	4.2	4.1
	2.05	1.83	1.94	2.15	1.85	1.54	1.77	2.00	1.94	1.85	2.00	2.16	1.86
50	5.1	5.1	5.9	5.6	3.9	3.4	4.2	5.4	5.8	4.8	4.7	5.1	5.0
	2.22	1.99	2.11	2.33	2.01	1.67	1.92	2.17	2.10	2.01	2.17	2.35	2.01
100	6.1	6.2	7.1	6.7	4.7	4.2	5.1	6.5	7.0	5.9	5.6	6.1	6.0
	2.53	2.26	2.40	2.65	2.29	1.90	2.19	2.48	2.40	2.29	2.48	2.68	2.26
200	7.5	7.6	8.7	8.2	5.8	5.1	6.2	7.9	8.6	7.2	6.8	7.4	7.3
	2.44	2.18	2.32	2.56	2.20	1.83	2.11	2.39	2.31	2.20	2.39	2.58	2.19
Freq.	8.8	8.6	7.5	8.9	6.5	6.4	8.0	8.5	8.6	10.3	9.3	8.5	100.0

z	Class 0		Class 1		Class 2		Class 3	
m	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}
10	5.8	218	4.0	88	3.5	58	2.8	28
25	6.3	278	4.8	139	4.3	102	3.6	61
50	6.8	338	5.6	194	5.1	150	4.4	98
100	7.3	442	6.6	308	6.1	235	5.3	156
200	8.1	627	8.2	613	7.5	458	6.5	293

Mission

To promote an innovative and environmentally sustainable technological development within the areas of energy, industrial technology and bioproduction through research, innovation and advisory services.

Vision

Risø's research shall extend the boundaries for the understanding of nature's processes and interactions right down to the molecular nano-scale.

The results obtained shall set new trends for the development of sustainable technologies within the fields of energy, industrial technology and biotechnology.

The efforts made shall benefit Danish society and lead to the development of new multi-billion industries.